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Metal multi-material additive manufacturing: Overcoming barriers to implementation

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ABSTRACT

Additive manufacturing has advanced rapidly since its origins in the 1980s. While some processes are now commercially viable, others remain experimental. A key ambition has been to combine multiple materials in a single part, enabling novel properties and overcoming traditional limitations of fabrication and assembly. Multi-material additive manufacturing offers a potential step change across industries, though scaling from lab to industry remains a challenge. This work explores the enabling technologies and science behind metal multi-material additive manufacturing and proposes how the research community can advance these innovations for meaningful industrial impact.

1. Introduction

From the inception of Rapid Prototyping (RP) to the emergence of 3D Printing and Additive Manufacturing (AM), users of technologies associated with these monikers have been driven to exploit geometrical and material freedoms to tackle engineering problems. While definitions and semantics cause significant debate (more of this later) "AM" will be used as the collective term for the purposes of this keynote paper.

Since the early 1980s AM has shifted from a niche laboratory family of processes to a multibillion-dollar industry which is now commonplace and a widely used household term [176]. Indeed, estimates suggest that 46 % of US based students majoring in engineering, mathematics, and computer science have used a 3D printer regularly [181]. In addition, 50 % of STEM students in America have interacted with AM or 3D-printed parts [182]. As such, if 3D printing is found in the lab, the factory, the home, and the hospital to name a few, perhaps the novice may consider AM a *written book*. However, this is far from the case and the hype surrounding AM continues to exceed the state-of-the-art.

Significant advances are apparent in the machine tool, material availability, design support, and skills associated with AM [262]. This has largely fuelled the rapid uptake of *consumer 3D printing* and niche industrial adoption. Yet, AM is still to reach an important frontier and exploit material design freedoms alongside the geometric. From the catalogue of "printable" designs available through open repositories such as GrabCAD [70] and opensource design tools available to all such as Blender [52] "geometry" in AM is a well-attacked problem. However, structures are comprised of both geometry and material in the real world. To this end, perhaps the most significant challenge to AM researchers is broadening the pallet of available materials beyond those used in conventional manufacturing techniques, and arriving at new combinations and formulations within the fabrication process. The state-of-the-art for monomaterials processing has been explored previously by the CIRP community in Bourell's well-used review on the matter [129]. Here, we seek to extend this for the benefit of the CIRP community and beyond to explore the realm of multi-materials process by AM.

1.1. Purpose and scope

The present keynote paper is intended to serve as a comprehensive insight into the state-of-the-art in Multi-Material AM (MMAM) – the convention we will adopt throughout this paper. In defining the scope of this the authors have drawn upon extensive consultation with Scientific Technical Committee "E" of CIRP (the International Academy for Production Engineering, or College International pour la Recherche en Productique) and evaluated prior contributions to the literature to capture the spirit of the field and present a vision for the future. In particular, the authors wish to add technical depth, breadth, and meaningful insight to help steer the community. For the benefit of a succinct and complete review, this paper focuses entirely on metal-based MMAM. The reader is referred to Bernard et al.'s perspective on the broader metal AM topic [19].

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It is clear from even a brief inspection of the literature that MMAM has been the subject of many summaries and reviews. The quality of these varies dramatically and as such the authority these may claim varies accordingly. Many of the reviews have been superseded by original research in this very active and growing field of inquiry. In the present consideration of the literature and, more importantly, the subsequent consideration of challenges and future research opportunities, the authors seek to provide perspective alongside opportunity such that the research community may branch out and address the key blockers preventing the advance of the state-of-the-art.

After careful review of the published literature, consultation with the community, and based on their own original research the authors have decided to focus on identifying the barriers to implementation of MMAM in which at least one metal alloy is being used. This helps to constrain the consideration offered in this review such that a full exploration can be offered.

1.2. Prior reviews of MMAM or similar

Nazir et al. [158] do indeed "systematically" review literature by summarizing findings but do not synthesize this information for driving research directions. The "Nazir review" while lengthy has several counterparts in the literature which are much more useful reads. For example, Han and Lee [80] explored the field in 2020 from a chemical engineering perspective and explored potential in electronics, biomedical and soft robotics fields. Meanwhile, much of this has now been superseded by original research.

The breadth of appeal across sectors of AM has also encouraged scholars from a range of disciplines to explore MMAM. Pajonk et al.'s [173] review of MMAM for architectural and building technology applications comprehensively explores the approaches and use cases for MMAM. While the field of interest is limited to a subset of architectural manufacturing technologies, the principles explored here in terms of process design stand true for the manufacture of all products. However, this work is somewhat lacking in terms of exploring the fundamental material limitations that will drive MMAM and considering the role that advanced design methods must play in taking this further.

A lengthy but less useful review in the opinion of the authors is available by Bandyopadhyay and Heer [13] which precedes the above works. Similarly, to the Nazir review it refers to a multitude of papers but does not examine the challenges or route to next steps the authors would propose the community to address. In general, the literature is awash with reviews of all topics and MMAM is no exception. Perhaps this is driven by emergence of readily available AI and library management tools rather than scholars seeking to distil the literature for the benefit of the community. The category of forgettable reviews also includes García-Collado's consideration of polymer MMAM [57], which lacks real insight into addressing challenges as opposed to phrasing them in simple terms.

Quality and process-specific assessments of the literature have been written. For example, Wei and Li [251] explore opportunities in Laser Powder Bed Fusion (LPBF) for producing parts comprised of multiple materials. This review explores in some details the machine tool design, energy material interaction, design and opportunities for this technology. Feenstra et al. [49] take a similar approach in assessing the contributions made in the realm of Directed Energy Deposition (DED). This includes an insightful consideration of the bimetallic interactions which are conceivable in DED across Fe, Ti, Al, Ni and Co-based alloys covering a majority of the alloys of interest in DED applications.

Multi-material reviews also extend beyond the specific manufacturing technology being used, but also seek to focus on a particular material type or application. For example, Putra et al. [184] and the excellent Schneck et al. [204] review report on efforts to explore Ti/Mg/Fe and the fundamental material challenges in realizing MMAM in metals, respectively.

The perspective offered by Zheng et al. [283] is most useful in shaping consideration of MMAM and the authors have subsequently made marked contributions to the field which are consistent with their summary of the field. Commentary is offered in relation to process physics yet to be enacted, but is of great value when proposing future research opportunities.

The authors were also able to identify numerous other reviews not worthy of mention, because they did not contribute any additional knowledge related to the state-of-the-art of MMAM or barriers to its implementation, hence they receive only cursory consideration in this sentence.

1.3. Evaluating research trends

When considering contributions to the literature from a macro perspective there is also value in considering seminal works (*see* Fig. 1) which punctuates the development of the metals segment of the field in the format of a timeline. In 1989, the first instance of multi-filament Fused Deposition Modelling (FDM) was reported. This represents an important step in considering the machine adaptation required to deliver two material feedstocks asynchronously, while limited to polymer/composite feedstocks only. This marks a first important step in the pursuit of MMAM.

Subsequent to this notable contribution, consideration is given to the first instances of metal-based MMAM. Most likely these were first apparent in contributions by Schlienger et al. [117] but metal-ceramic cladding or primitive weld overlay likely predates this by some time. More recently, the emergence of multi-material delivery in powder bed fusion has become an intense area of research. The first industrial apparatus for this purpose, a multi-powder re-coater, is designed and manufactured by Aerosint [15,3]. The design capability which has moved in parallel has allowed increasingly complex material arrangements to be contemplated alongside advanced structures. Examples have been included in Fig. 1. It is immediately apparent to even the novice that this topic of research is developing rapidly and offers a wealth of opportunity for research at the confluence of manufacturing, materials science, design and process physics.

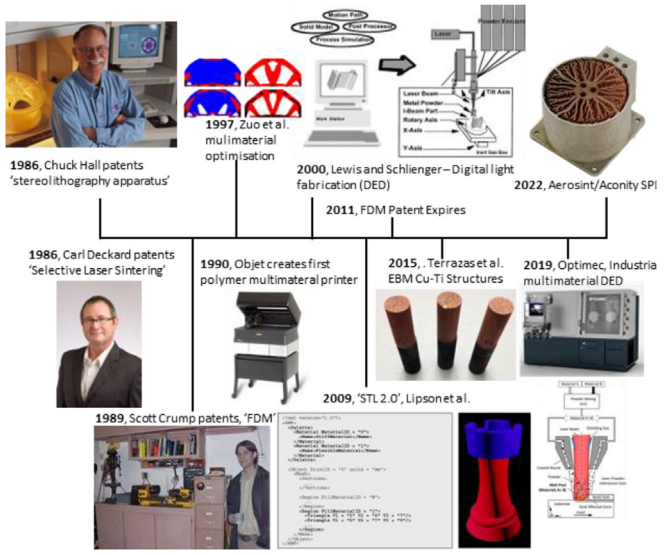

Fig. 1. A concise timeline of notable contributions to the literature and industry in MMAM not limited to metals only. These contributions have secured the interest of the research community and given rise to a growing body of research in the field.

1.4. Semantics and context

It is important for the purposes of this manuscript that the authors settle on terminology which will be consistent from hereout. Much of this has been inferred from the literature and has been summarized in Fig. 2. Here, a progression in complexity and hence manufacturing difficulty is proposed working from left to right (left being most simple). A single or mono-material delivery system is most observed in modern AM systems. Marginally more difficult than this would be

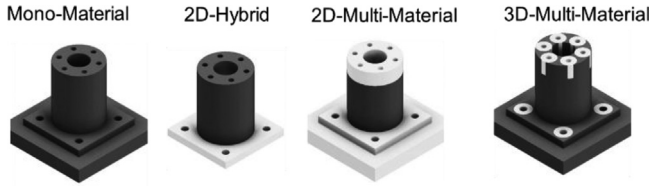

Fig. 2. A graphical representation summarizing the conventions and terminology used in this work covering principle MMAM deposition types ranked from least difficult (left) to most challenging (right), according the [22].

the "2D-Hybrid" approach in which individual materials may be built on top of one another. Repeating this on multiple occasions within a single build constitutes "2D-Multi-Material" additive manufacturing.

Developing this still further and being able to modulate material composition within 3D dimensions comprises "3D-Multi-Material" additive manufacturing. In the remainder of this review the authors will refer to the final two as 2D MMAM and 3D MMAM. Process peculiarities mean that there are some local aberrations to this rule. This is not considered at length in the Raffie et al. survey [186] of the subject area, which includes a collection of excellent illustrations relevant to the geometrical challenges associated with MMAM. The authors propose the convention of Fig. 2 as a useful means to efficiently describe the geometrical considerations in MMAM.

Developing this further, one must also consider graduation of materials (e.g., variable blending along a vector) to fully exploit the opportunities of machine tools capable of vectoring material delivery. While the interface regions illustrated in Fig. 2 are convenient (they are step functions) from a design and semantics perspective, very rarely do we see such stark contrasts in material properties or composition. Nature's solutions to engineering problems requiring multiple material properties rarely manifest themselves as step changes, but rather as graduated functions. As such the transition between constituents in MMAM is a key concern. This is illustrated for DED in Fig. 3a where graduation is engineered in the Z direction of a simple thin wall structure.

At this stage of the introduction the reader may wish to better explore the rational for combining multiple materials into single metallic components. Since the literature is awash with the opportunities for dissimilar welding [48] to produce multi-material fabrications the application of a scaled approach in AM seems both feasible and with merit. However, opportunities which currently justify the cost and complexity of MMAM are often limited to the high-value sectors such as aerospace, biomedical and tooling. In addition, we will understand through the course of the review that while several example opportunities for MMAM have been identified there are scarce examples of scaled use of this technology. Perhaps a key element of this review is to help understand why and better navigate the challenges limiting its progression.

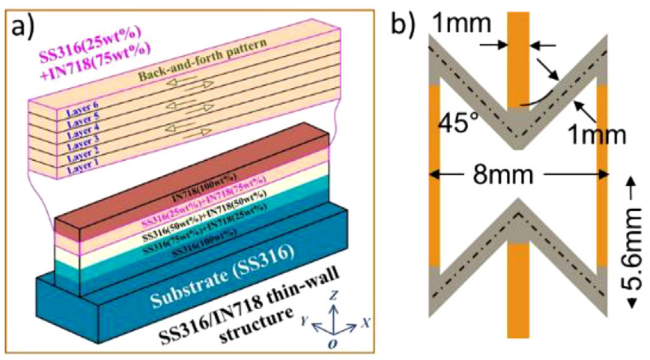

Fig. 3. a) A simple "continuous" blending of composition in the build (z) direction using DED (courtesy of X. Jin, UBC) b) Recent contributions to STC-E (courtesy of M. Bambach, ETH) showing the intricacy of structures which may be fabricated by LBPF but the challenge of controlling volumetric deposition is apparent.

1.5. A guide to using this review

While there is a desire to thoroughly review the literature here such that the reader has a comprehensive understanding of the state-of-the-art, the authors also wish to illustrate how MMAM can be used to address emergent engineering challenges and highlight opportunities for research to enable society assisting technologies. The cumulative number of contributions to the literature (>>3000 and growing) and the small percentage of which meets the quality threshold of leading journals,(<20 %) means that many papers will not be considered here. The authors trust the reader will be sympathetic where inadvertent omissions have been made. This work also assumes some basic knowledge on the part of the reader with regard to standard AM machine configurations and their limitations. A useful introductory source where required has also been previously published from within STC-E [28].

2. Opportunities for metal multi-material AM

It is apparent that there are significant opportunities for MMAM in emergent sectors although these are not always apparent to designers accustomed to traditional manufacturing methods. For MMAM to become a deployable technology which serves to solve engineering problems at scale, applications which benefit from the use of these technologies (in terms of the traditional manufacturing metrics of cost, quality, time, sustainability, and part properties and performance) must be assigned. In preparation of this manuscript, while there was significant exploration of process and materials science associated with MMAM in literature (e.g., Fig. 3), there are few reports which demonstrate significant manufacturing advantage by the criteria listed above. As such, we endeavor to highlight below five opportunities for MMAM in the form of illustrative case studies.

2.1. Case study 1 – aerospace engineering

The aerospace industry may be characterized by its focus on innovation tempered by stringent safety standards. The sector includes the development and manufacture of aircraft, spacecraft, satellites, and related systems for both civilian and military applications. Aerospace industry receives constant pressure to produce more fuel-efficient and less polluting aircraft both from a commercial perspective as well as from regulatory bodies [147,25].

As MMAM allows for the simultaneous use of different materials within a single component and in a reduced number of processing steps, this opens up new possibilities for creating complex shapes with varying (material) properties in different regions of a part. As such, multi-material parts may offer advantages over single-material parts like e.g., enhanced structural, thermal and corrosion properties [236]. The aerospace industry is keenly interested in such capabilities due to the significant impact weight has on fuel efficiency and therefore cost of running the asset. Engineering designs that optimize for both weight and performance hold promise for cost reduction [65,78]. Although the field is emergent, MMAM is potentially capable of overcoming traditional barriers and is hence regarded as gamechanger.

Aeroengine components (propulsion) – Within aerospace (gas turbine [205] and rocket [93]) engines components are subject to extremes in terms of temperature and pressure. As such it is desirable to withstand these loads while also providing more nuanced material properties such as thermal conductivity and resistance to corrosion. These drivers have been pivotal to the formulation of "substrate" alloys [165] and advanced Thermal Barrier Coating (TBC) systems [74] which have notably advanced propulsions systems. MMAM in due course may be used to manufacture these complex, heterogeneous structures for aircraft engines. This includes parts with intricate internal structures, cooling channels and optimized material combinations to withstand high temperatures and mechanical stresses. Ni-based alloys are essential for aeroengine applications due to superior properties as high toughness, hardness and strength at extreme temperatures next to having excellent corrosion and oxidation resistance [4]. Monolithic engine parts that see a large temperature range

across their geometry intrinsically have a portion where material properties and structures are carefully selected since they are mission critical. Such parts are challenging, but potential use cases of interest for MMAM. Hence, typically material combinations here are lightweight Al and Ti alloys joined with Ni-based superalloys [164]. In LPBF a 1D material transition can be realized by changing the material properties of subsequent layers during the powder deposition stage. For instance, by premixing the powder feedstock, defect-free grading was achieved up to 20wt % inclusion of IN718 in Ti6Al4V to achieve a crude bimetallic transition between a turbine blade's core, where temperature is relatively low, and the vane, which is exposed to the high temperature environment, *see* Fig. 4a [200]. While the integrity of this may be questionable, it does serve to illustrate a degree of capability with significant potential. Bimetallic interfaces are generally acknowledged as a weak link because of local compositional variations and the stress concentration resulting in interface cracking [185], and are therefore often researched for various AM processes: e.g., DED, Wire Arc Additive Manufacturing (WAAM) [185], Laser Metal Deposition (LMD) [153]. For LPBF, when gradually transitioning from pure Ni to Ti, intermetallic phases occur in the graded zone, where also cracks are found [41]. The formation of unfavourable oxides (within the Ti constituents) and the formation of intermetallic in the Ti-Ni system serve to make the metallurgy of such unions complex [225].

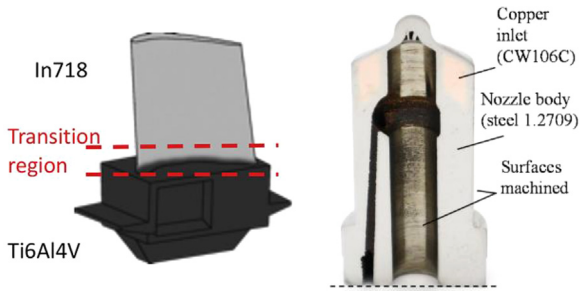

Fig. 4. Aeroengine MMAM concepts reported in the literature. The reader's attention is drawn to the primitive geometries explored to date and the root challenge being weldability in heterogenous processing. a) turbine blade concept with 1D material transition [37]. b) injection nozzle concept with 3D material grading [42].

Similarly lower-cost Stainless Steel (SS)-based alloys may be joined with higher-cost Ni alloys, due to the high solubility of the principle elements (Fe, Cr and Ni) [216]. Cladding of low-cost steel grades with superior Ni based coatings has been widely reported [2] and enjoys widespread industrial usage. Grading SS316L and IN718 exhibits good metallurgical bonding, although adapted LPBF processing parameters are advised due to the appearance of some cracks and holes at the interface [135,145]. Also, using DED SS316L and IN718 can be joined although due to dilution a 500 μm thick composition gradient material zone exists in which fine cracks are present [197]. SS316L has been functionally graded with Cu10Sn to make aircraft engine disks featuring a smooth transition between both materials [253]. Although once again the integrity concerns around such systems likely means their utilisation is limited at this point.

To reduce wear on rotary components, the high-pressure compressor section of engines may receive a metallurgically bonded CoNiCrAlY (or similar) protective coating on IN718 using LPBF [126,127]. Similarly, using DED a Ti-Si-N ceramic coatings may be deposited on Ti, where microstructure and phase changes determine the coating's hardness and wear resistance [282]. Also hard elements such as tungsten can be functionally graded with SS316L using LPBF to obtain high hardness and radiation shielding properties [284]. In addition, Cold Spray (CS) technologies have been used to perform similar duties [32]. Of note here is the rapid emergence of CS as a technique capable of depositing at volume in true 3D form [276].

With the use of LPBF combined with a more complex powder deposition mechanism, full 3D material grading can be achieved. The recoater locally deposits the required set of materials within each layer similar to a conventional multi-color inkjet printer. For efficient cooling of fuel in an injection nozzle, high-conductive copper is placed the injector tip, as shown in Fig. 4b [251]. Here, a 3D material transition from carbon-rich tool steel to copper CW106C was realized, and a quality comparable to single material LPBF was claimed.

In rocket engine design IN718 is the material of choice to assure mechanical integrity at elevated temperatures while offering acceptable weldability and machinability. By locally inserting a higher conductive material, such as aluminium, the inner thermal flow structure may be improved [128]. Similarly, titanium and tantalum, and IN718 and copper-alloy GRCop-42 have been fused in 3D [245]. Further, authors have reported copper-chrome-zirconia and tool steel in combination [9]. The material composition during melt pool mixing and solidification differs for in-plane (horizontal) and layer-to-layer (vertical) material transitions resulting in directionally dependent thermal histories and complex microstructure formation in the transition zone between materials. This factor has been the focus of much of the quality work in the discipline.

Heat exchanger and ducting systems – Aircraft often require intricate ducting systems for air and fluid flow, and thermal management. MMAM may be employed to produce these systems ensuring durability, thermal conductivity and optimal fluid dynamics. Following a 1D material transition, heat exchanger concepts, as shown in Fig. 5a, are feasible [259]. IN718 is applied at the high-temperature section and lower-cost SS316L is applied for the lower temperature regions where superior mechanical properties may be required. Similar concepts exist for DED where a functional grading can be realized using direct deposition or a compositional grading by varying powder blending at the material interface between copper and SS304L [269] or between IN718 and copper-alloy GRCop-84 [170].

Fig. 5. Heat exchange and ducting MMAM concepts reported in the literature. a) Heat exchanger concept with 1D material transition [58] b) complex ducting concept with 3D material grading [63].

In [22], the transition zone between SS316L manufactured by LPBF and IN625 generated via DED was analysed regarding defect formation and microstructural characteristics. Two processing strategies were investigated: On the one hand, IN625 and SS316L powder were premixed in DED. On the other hand, a direct transition was generated by directly depositing IN625 onto the SS316L substrates. Premixing the powder materials resulted in a promoted defect formation. Fe-enriched zones within this mixed transition zone were characterized by elemental segregation. Less defects were obtained when depositing IN625 directly onto the stainless-steel substrates. Immiscible metals can also be joined using a third interlayer or buffer material; e.g., Ti-6Al-4 V and SS316L can be joined by Electron Beam Melting (EBM) using copper in between to suppress the formation of iron-titanium intermetallic compounds [285].

For more complex heat transfer and ducting applications, 3D material grading is utilized to further enhance performance. Fig. 5b shows a fluid-driven MMAM burner nozzle concept in which copper is locally added with respect to the single-material IN718 counterpart. In this concept, thermally loaded regions benefit from being constructed using materials with higher thermal conductivity [192].

Relatively simple heat sink structures benefit from multi-material grading. Forced-convection pyramidal fin arrays with a steel leading

edge and an aluminium trailing edge around a nickel section fabricated by cold spray AM demonstrated a 35–42 % performance increase in thermal conductance compared to the single-material SS304 counterpart, although the resulting surface quality reportedly also affected convective heat transfer which must be figured in future designs [38]. As AM technologies in general deliver parts in near net shape condition with relatively rough surfaces, this benefits thermal management solutions rather than hampering. More complex, numerically optimized heat sinks with copper dendrite fins within a stainless-steel body fabricated by LPBF have also been reported [120].

Lightweight structural components – Aerospace companies are also exploring the use of MMAM to create lightweight structural components for aircraft wings, fuselage sections, and other critical parts. Bi-material systems are being pursued to fabricate lightweight, integrated, multifunctional structures [79]. By optimizing material combinations, these components can achieve a balance between strength and weight savings. Here, MMAM is an enabler for reaching sufficient structural stiffness, minimize mass and potential incorporation of energy storage solutions compatible with the future of aerospace. The application of multi-material thin-walled structures require a material-structure integrated design method [280]. Improved flight efficiency is expected from morphing aircraft wings, allowing in-flight configurational changes. This may require smart-material structural components [220]; e.g., tuneable energy absorption multi-material lattice structures [156].

Lightweight structural components can also be made by reinforcing lightweight metals. Metal-matrix composites ideally combine metallic properties like toughness and ductility with rigid, stiff and wear resistance ceramic properties. By pre-blending metal powder with reinforcement ceramic particles metal-matrix composites can be fabricated using LPBF [100]. Aluminium, titanium, and steel-based composites are formed during solidification of the melt pool. For some material formulations, the laser irradiation of the LPBF process may trigger an exothermic chemical reaction resulting in superior material performances [40]. Alongside common aluminium-based metal-matrix composites [39], also magnesium may be reinforced using silicon carbide [261]. Similar approaches using DED with pre-alloyed powder have been reported to build up metal matrix composite; e.g., using Al-Si alloys [45,44], or using CS [267].

Satellite components – Components for satellites and other spacecraft may benefit from the flexibility offered by MMAM in the future. This includes sensors, instruments, housings, and structural elements with varying material properties tailored to the specific needs of each part. In addition to these use cases, one particular space requirement due to exposure in cyclic solar radiation is a material behavior tailored to a near zero Coefficient of Thermal Expansion (CTE). Nickel-iron alloys, such as Invar36, have this ability and are ideally suited for space instruments, large scale space telescopes, optical devices and cryogenically sensitive equipment. To reach near zero CTE parts may feature a combination of geometric features, such as lattices, and material properties, which could be fabricated via (a combination of) additive processes [278].

One MMAM process chain suitable for satellites uses EBM to fabricate Ti-6Al-4 V parts after which CS is used to deposit an Invar36 structure to meet requirement for an optical support structure for a nano satellite application [140]. For similar reasons, LPBF of Invar M93 on A36 steel has been investigated. At the surface of the fabricated sample the CTE could be reduced by 42 % compared to the original steel [11]. Also, Invar36 and SS316L have been processed previously by LPBF. Here, a critical laser energy density was found for which part properties are nearly in line with wrought material [270]. Functional grading can also be obtained by pre-mixing Cu10Sn powder with increasing Invar36 content and LPBF processing. Low laser absorptivity, high thermal conductivity and low melting point of the copper-alloy led to the inclusion of partially and entirely un-melted Invar36 particles particularly in the lower level of the powder layer. Also, at higher layer thicknesses, useful for time-efficient fabrication, more inter-layer defects occurred [73].

The heat shield or Thermal Protection System (TPS) of space shuttles may also benefit from using MMAM [237,238] in a similar fashion to aerospace TBCs.

Sensors and electronics integration – MMAM allows for the combination of metals and polymers in a single component. Relatively simple parts may have a metal frame for structural support combined with a polymer outer layer for impact resistance or thermal insulation, while more complex fabrication techniques may enables the integration of sensors and electronics directly into 3D-printed components. In aerospace, this has been applied to create components with built-in sensors for structural health monitoring, temperature sensing, and other functionalities. Metal-ceramic multi-material fabrication may be utilized to fabricate novel types of antenna structures. Fig. 6 shows a single component wideband monopole antenna fabricated by multi-material extrusion AM and microwave sintering [69]. Here, the conductive metal is silver powder and the dielectric body is silver molybdenum oxide. Also, Selective Laser Burnout (SLB) has been used to fabricate Radio Frequency (RF) and microwave communication components [64]. In this case, conductive silver powder and bismuth molybdate are used for the conductive and dielectric material, respectively. Similarly, by inkjet printing using dielectric and conductive inks (containing metal particles) electronic components such as printed circuit boards and antenna elements can be fabricated with full 3D design freedom and enhanced robustness [243,179].

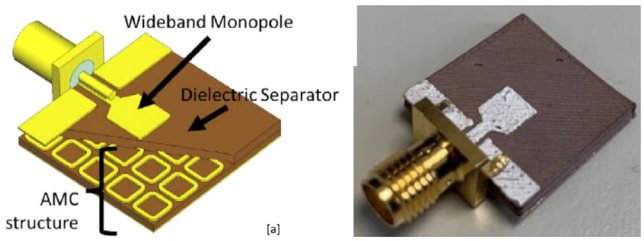

Fig. 6. MMAM concepts for antennas. In this case a wideband monopole antenna concept [84], fabricated as one single part by multi-material extrusion and microwave-assisted sintering, is illustrated.

2.2. Case study 2 – MMAM for biomedical applications

The number of materials certified for medical applications is continually growing. Driven by an aging population and growing middle classes around the world, the demand for advanced medical technologies continues to grow. For example, multi-material bioprinting has emerged in this sector due to its high versatility. Microfluid bioprinting appears to be a promising technology for the generation of e.g. soft tissue structures through multi-material printing by introducing secondary phases [191]. In [194], porous multi-material structures were fabricated generatively for nasal reconstruction. It was found that cell viability was affected significantly by the applied processing parameters, mainly UV exposure.

Extrusion-based technologies also support the fabrication of multi-material products for medical [21]. Hybrid tissues can be manufactured by alternatively depositing thermoplastic fibres and hydrogels [207]. Using thermoplastics, an encapsulating structure can be fabricated, which can be filled with different hydrogels – independent of the mechanical properties or inherent stiffness of the applied hydrogel.

Returning to metal AM, the takeaway message is that multi-material production opens enormous potentials for biomedical applications. In the field of metallic materials, the main alloys used include cobalt-chromium alloys, stainless steels, and titanium alloys. These materials can be categorized based on their primary properties like corrosion resistance, biocompatibility, strength and wear resistance, among others [228]. From these properties, it becomes evident, that properties like ductility and biocompatibility result in a trade-off. Highly ductile parts typically possess a lower biocompatibility, and vice versa. However, there are seemingly many applications where designers may wish to exploit these properties in parallel necessitating a consideration of MMAM.

Considering the intrinsically different material properties, a multi-material manufacturing approach could help to overcome the

limitations of mono-materials. Combining ductile alloys with wear-resistant material systems allows for a more specific tailoring of the final implant properties [221].

MMAM provides an additional degree of freedom in the design of the implants. For example, the use of alloys with different densities and mechanical strengths allows to even further optimize the weight and spatially resolved part properties [13]. In the long-term perspective, it could also be possible to manufacture metal implants with a tailored biocompatibility, e.g., using resorbing materials, or with integrated sensors, e.g., for the in vivo detection of inflammations in early stages [94]. Modifying titanium through the addition of tantalum for example helps to adjust the Young's modulus of the material through the transformation from an alpha-phase-dominated material towards a beta-phase-dominated one [214].

A promising approach for modifying the in vitro properties of the materials is provided by the addition of Cu to Ti-6Al-4 V. Higher Cu concentrations result in an increase of the antibacterial rate to values of up to 99.99 % [75]. Potential applications could be the adjustment of bone replicas through a targeted alloy modification to improve the osteogenic response in the future.

Another work [111] focused on the degradability of biocompatible Mg-alloys. Depending on the alloy composition, it was possible to tailor the degradation time from a few weeks up to one year. Linking this approach to MMAM would support the fabrication of biodegradable structures with spatially resolved degradation properties. This approach would be helpful when targeting good degradation properties while also maintaining a sufficient mechanical integrity.

In all cases, the transition zone between the two materials needs to considered as one of the most critical regions [258]. Brittle microstructure, which could result from poor compatibility of different materials, would support a premature failure of the implant. Adapted processing strategies are consequently required to achieve not only multi-material parts but also parts with an at least comparable longevity [217].

A multi-material approach here opens new potential regarding the tailoring of the patient's well-being. In dentistry, the limited thermal conductivity of additively generated implants promotes discomfort at extreme conditions [174]. Locally introducing materials with an improved thermal conductivity would help to alleviate thermally aggravated discomfort. A comparable approach is followed by Fidentis for the generation of customized dental implants using multi-material LPBF.

A significant implementation barrier here is the time required for the certification of new materials. Currently approval processes for implants are specific to mono-material implants and as such acceptance of MMAM technology requires a new approach to certification to emerge.

Considering the potential of multi-material implants, spatially optimized implants can be designed. To assure the biocompatibility of the final part, the surface of the implant can be made from certified materials [122]. The new possibility lies in the field of tailoring the internal bulk materials by modifying the chemical composition or adding secondary phases, which is often done in tissue engineering or bioprinting.

It needs to be considered that the design of such implants requires a precise handing of the additional elements to avoid cross-contamination effects in MMAM [16]. Otherwise, the material composition may deviate from specification.

Though the number of examples is quite large in the field of bioprinting and tissue engineering, MMAM using metallic materials remains and emergent field.

2.3. Case study 3 – multi-material tooling

One industry that profits heavily from AM is the tooling sector [106]. For example, [104] provides an overview of the potential of mainly mono-material AM techniques for cutting tools applications including tool materials like High-Speed Steels (HSS), tungsten carbides with cobalt matrix (WC—Co) and ceramics. Besides these materials for tool substrates, investigations on materials for tool carriers like Ni-based superalloys, Co-Cr alloys, tool steels, stainless steels, Ti-, Al-, Cu-, and Mg-based alloys, precious and refractory metals, intermetallic compounds, and high-entropy alloys are described. Establishing an AM process chain helps to reduce the average lead-time for tool fabrication [90]. Furthermore, worn tools can be refurbished using regenerative technologies such as DED. A first step in the area of MMAM for cutting tools using DED processes was demonstrated in [215] where a tungsten carbide tool insert was manufactured to introduce flexibility and customization in machining industries. Crack-free deposition of 88 wt %WC and 12 wt %Co was obtained at 800 °C high-speed steel substrate-preheat temperature. An insert was dimensioned and progressive turning of Aluminium 6061-T6 alloy was performed. The use of highly resolved AM processes such as LPBF supports the generation of conformal cooling, which helps to reduce both cycle times and tool wear during serial production [107]. However, most of these tools are made from mono-materials. Introducing multi-material approaches could provide an additional lever in tool design that currently does not exist. This becomes obvious when breaking down the key demands for tools [274]: (a) high strength to avoid mechanical wear, (b) good thermal conductivity to remove process temperature, and (c) good corrosion resistance to assure longevity of internal cooling channels. However, not all of those properties can be matched to a theoretical optimum when selecting only one material. For example, the maximum strength (e.g., surface hardness) typically limits the corrosion resistance of the material [226]. Tool steels therefore possess a poorer corrosion resistance than stainless steels. On the other hand, highly conductive materials like aluminium, copper, and silver do not meet the required properties of tools that are used in serial production where tribology comes into play.

Considering this, the application of multi-material manufacturing supports the tailoring of the tool properties by selectively modifying the chemical composition in different regions of the part [17]: see also Fig. 7. The high-strength material can be limited to regions that require a high-wear resistance [202]. Typically, the high carbon concentration promotes defects like pores - *and even worse* – cracks [196]. By only selectively using these materials (e.g., tool steels), the processability can be improved since only moderate volumes of the hard-to-weld materials are processed.

One of the most important aspects in MMAM is to assure the compatibility of the different materials that are used during processing [29]. For processing these material combinations, two of the most promising manufacturing technologies are LPBF and DED. LPBF supports the generation of highly sophisticated parts (e.g., with internal cooling structures). However, poor thermal control during processing limits the processing of hard-to-weld materials due to a promoted crack tendency [54]. In contrast to LPBF, DED can be successfully used for processing materials that are more prone to crack formation. However, the larger melt pool sizes reduce the overall resolution that can be achieved during build-up and secondary processing will thus be required to deliver high-resolution features [172]. Moreover, downfacing surfaces and hence also internal channels are hard or impossible to produce in DED.

Steel-Steel-Gradients - One important factor for improving the corrosion resistance is the generation of steel-steel-gradients in a multi-material process. In this case, the transition zone between the high-strength tool steel and the corrosion-resistant steel needs to be

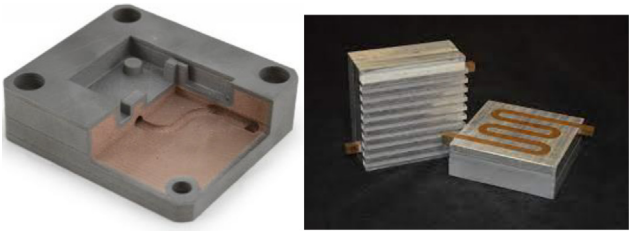

Fig. 7. An example of a multi-material injection molding tool comprising a hard steel outer case for wear resistance and a copper-based core for enhanced thermal cycling performance [110].

tailored to avoid the formation of undesired, brittle secondary phases that could lead to a premature part failure [5].

In tool design aimed for AM processes, the volume of crack-sensitive or difficult-to-weld materials should be maintained at a minimum to obtain the best results. Consequently, the volume of the tool steel should be kept at a minimum. One important aspect, like for the other case studies we have explored, is the microstructure formation at the interface between the two materials [137]. Inappropriate material combinations can promote crack formation or poor fatigue performance due to the formation of brittle phases [264]. The generation of gradients from stainless to tool steels can be characterized by undesired secondary phases [171]. Approaches for countering undesired microstructures are provided by adjusted processing strategies in the transition zone. By increasing or reducing the energy input, the size of the dilution zone can be tailored to achieve flexible chemical compositions within the dilution zone. In combination with the thermal boundary conditions, that are affected by the processing strategy, the microstructure can be adjusted [137].

Another, perhaps less efficient approach, is the use of a buffer material that does not form undesirable phases when welded with dissimilar materials [188]. The limitation is that one more material needs to be supplied to the process zone (e.g. in multi-material PBF or DED), which drives up machine and hence process costs.

Steel-Copper-Gradients - The industrially most relevant concept for improving the cooling performance is to introduce copper due to its excellent conductivity. Adding copper can be beneficial to increase the thermal conductivity of the tool being produced. The improved heat transfer is again beneficial to reduce the cycle time and thermally induced wear. One important aspect that needs to be considered is the compatibility of the steel matrix with the introduced copper [255]. While excessive copper concentrations promote defect formation, too low concentrations might not result in a sufficiently improved cooling behaviour of the final tool [224]. Furthermore, the difference in CTE influences multi-material interfaces and lead to either local compressive or tensile stresses, something that must be compensated for in design or post processing [63]. Appropriately selecting the material pairing based on these thermos-physical properties provides another lever for tailoring the performance of the tool. For example, additionally introduced compressive stresses can be beneficial to reduce tool wear. However, this demands an exact knowledge about the underlying thermal boundary conditions and stress states during operation.

Metal-Ceramics-Composites - One final optimization potential lies in the generation of multi-material or reinforced surfaces. The addition of hard phase particles like carbides [7], oxides [92], or nitrides [232] can help to increase the surface hardness and the wear resistance of the part. These particles are dispersed within the matrix. The result is a Metal-Matrix Composite (MMC) with modified properties that are caused by the secondary phase.

It has been shown that hard particles help to improve the hardness and wear resistance of many different materials, ranging from stainless steels over tool steels to titanium alloys. Much of this understanding draws upon classical approaches to weld overlay and laser cladding. The approach of hard/reinforcement particle addition is promising in regions that are exposed to conditions favouring wear during operation of the tool. Consequently, tools commonly used for forming could be reinforced to possess less wear and thus improve the average lifetime [99]. Introducing hard particles helps to reduce undesired adhesive and abrasive wear. For example, the hard particles are less susceptible to cold welding effects compared to a homogeneous metal matrix when using those tools in die forging. One issue that needs to be considered is the bonding of the hard particles to the metal matrix [17]. A non-sufficient bonding could result in a premature failure, promoting a deleterious effect.

It may be that industry seeks the generation of metal-ceramic-transitions within one part [246]. The ceramic structure could act as an electrical or thermal insulator. This possibility opens the potential for the integration of high-precision sensors within one part. However, the limitations are obvious: different and almost contrary thermal properties of steels and ceramics lower the compatibility even further. To exploit this concept, an understanding of MMAM with more compatible elements needs to be established in the first instance.

The main conclusion that arises from this case study is the problem of compatibility of the materials used in MMAM. Key parameters are CTE mismatches, which also need to be considered during the final application, as well as the solubility of the different elements within the matrices.

2.4. Case study 4 – electrical machinery

Rotary electrical machines, i.e., motors and generators, have become one of the major prime movers of the modern world, and static electrical machines, i.e., transformers, have become an essential part of the world's future energy infrastructure. This section considers the design and manufacturing of electric motors enabled by MMAM.

Electrical machines are highly efficient with efficiency levels reaching ≥95 % for various motor configurations. They require very little maintenance and are highly robust as a result; the field has been in stagnation for quite some time with designs varying modestly from early concepts. This has changed with the growing interest in electrification of our transportation system as part of wider strategies to mitigate climate change. The demand for high-efficiency and power-dense electric motors is increasing significantly. Electric motors can account for nearly 70 % of the total power consumption of a manufacturing facility. In fact, electric motors in general consume 45 % of global electric energy [244].

In addition to the ever-present requirements for power density and efficiency, the implementation of electrical motors in various vehicles has created new design and performance requirements, such as limitations on motor volume, shape and weight. High performance motors are now required to also be manufactured cost effectively at high volumes. Reports estimate that there are 600 million high-performance AC motors in operation around the world [190]. The sheer number of units in existence and the growing demand has pulled geo-political and global supply chain consideration into design and manufacturing decision making. These forces are pushing towards elimination of rare-earth permanent magnets from the design and manufacturing process. This will apply even harsher restrictions on engineers to maintain efficiency and performance metrics with a reduced dependency upon these strategic materials.

To better understand the impact of MMAM on design and manufacturing of electrical machines we must first gain an understanding of the conventional manufacturing processes involved. Typically, a series of design standards coupled with sophisticated simulation and modelling tools are used to determine the type of the motor suited for the task and the details of the principal components of the motor. An electrical machine, regardless of type, consists of five principal components: shaft, rotor, stator, windings, and housing. Fig. 8 shows an example of an electrical machine and its components. Rotors are typically machined from a steel alloy rod. Rotors and stators, sometimes called machine cores, are made of ferromagnetic, or soft magnetic, materials. FeSi, FeNi, or FeCo are examples of such materials with FeSi being the most popular [114]. Sheets of soft magnets are produced through cold-rolling processes. Sheets are then electrically insulated using various coating processes. Insulated sheets are then cut to shape using laser cutting or punching to form laminates. In the final step, the laminates are stacked and mechanically interlocked via stamping to form the rotor and stator. Windings are multiple turns of conductor wire, usually made of pure copper and in some instances, aluminium. Windings can come in form of an insulated wire with various diameters depending on the design requirements, and in form of stacked plates or thick bars known as hairpins. Conductors are manufactured through a drawing process. Drawing is done through multiple steps to reduce the diameter of the wire for different gauges. After drawing, the wire is electrically insulated through a chemical coating process. Finally, the housing for an electric motor is commonly made using casting or machining depending on the size of the motor. Finally, these components are

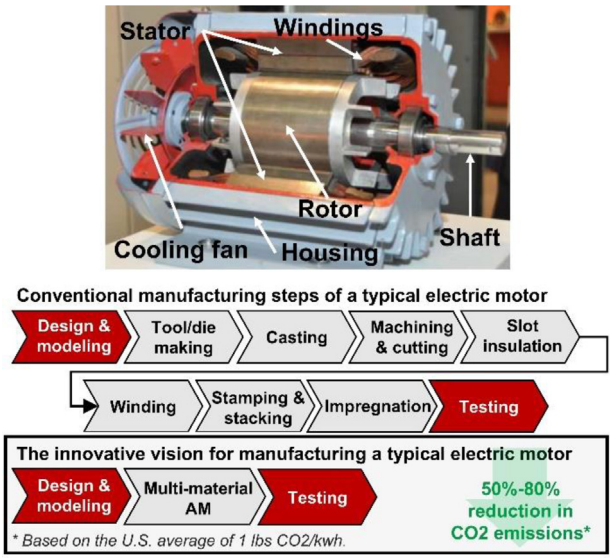

Fig. 8. A comparison of conventional and proposed manufacturing steps involved in electric motors production (left). The CO_2 emissions estimate incorporates the energy consumption for feedstock and manufacturing processing, and material waste factors [130]. An example of an induction motor with its major components (right).

gathered at the assembly location where the motor is put together to start its testing and verification process. The assembly process can be fully or partially automated depending on the motor and facility type. Fig. 8 depicts a high-level view of possible conventional motor manufacturing processes. Different representations of this process with varying level of details can be found at [114,239,187]. Considering the multi-step process chain mentioned above, there can be as many as five different processing and manufacturing plants involved in producing an electric motor. These plants make part of a complex global supply chain for electric machines.

The conventional motor design and manufacturing process poses the following challenges: 1) The distributed nature of these processes can result in long lead times for design and manufacturing of motors making it ill-suited for rapid iterative design and modification cycles favoured by design engineers today; the process for a newly configured motor can take anywhere between 6 months to a year to be established. 2) These conventional processes are inherently unfriendly to customization or design change implementations. 3) They provide limited design freedom; for example, implementation of 3D magnetic flux paths in rotors are known to be beneficial but are almost impossible to manufacture using the conventional methods [272,97]. 4) The multi-step process chain can leave a significant manufacturing carbon footprint rendering electric motors an ineffective tool in our toolbox to combat global warming. It is our view that MMAM, when fully implemented, can effectively address the above-mentioned challenges posed by conventional processes: *see* bottom inset of Fig. 8.

Facing new design and performance requirements, the community was quick to adopt AM. Early efforts were centred around feasibility of using AM to produce components of an electric motor [234,98,271,115,61]. The second phase of research was focused on taking advantage of design freedoms that AM has to offer to generate new designs for windings [36,265,213,125] and cores [230,60,235] followed by machine prototype testing [167,231]. As the implementations matured, a more holistic approach to utilizing AM for design and manufacturing of electrical motors emerged [231,199]. MMAM, as defined in this work, started to evolve in parallel and the first mentions of MMAM for electrical machines started to appear [239,222]. As of today, MMAM for electric machines has hardly been implemented in any real production capacity with an exception of a few preliminary attempt to manufacture and characterize a synchronous reluctance rotor [163]. The mentions of the term "multi-material AM" can often be found at the conclusions' sections of research papers as a potential ground-breaking solution. Even then, the vision for the use of MMAM is often limited to part-scale applications, such as eddy current reduction by printing an insulating layer for machine cores [239,210]. Although the eddy current problem deserves attention, it is hardly the whole picture when it comes to MMAM.

When fully implemented, MMAM can fundamentally change how electric motors are designed and made. The key enabler to this fundamental change is the ability to bond soft magnetic materials, pure copper, and an electrically insulating material, e.g., ceramics, in a single additive process. Fig. 9 depicts the three multi-material bonding scenarios required to realize this vision. This approach will move the design and manufacturing of electric motors away from a multi-step process chain and towards a Single-step Motor Manufacturing (SiMM) process. Using SiMM, the principal components of an electric motor can be manufactured simultaneously within the same additive process. SiMM can give rise to a new generation of motors that can potentially exhibit superiority over conventional machine designs in the following categories: 1. power density, 2. efficiency, 3. structural integrity (strength and stiffness), and 4. design freedom. Furthermore, MMAM of electric motors can have cascading effects across the industry value chain by: 1. Reducing development lead time from months to weeks, allowing faster design iterations. 2. Reducing technological footprints by reducing manufacturing steps and consequently reducing the carbon footprint of electric motor manufacturing. 3. Reducing the need for complex assembly and joining operations by part consolidation. 4. Supply chain simplification by enabling vertical integration of the manufacturing process. The potential groundbreaking impact of SiMM merits concentrated multi-disciplinary research and development supplemented by industry collaborators to overcome the serious technical challenges facing its full implementation. There are significant challenges facing the realization of SiMM process. This section will briefly identify and describe the main barriers. The current state of the art AM technology applied to design and manufacturing of electric motors are to date separately realized in each individual motor component. Some examples include windings for switched reluctance motors [125], a lightweight rotor for a permanent magnet synchronous motor [115], shaped profile windings for minimal AC loss [213], and a free-form design concept of rotor cores [60]. The researchers seem to agree that AM technology has the potential to transform the design and manufacturing of electric motors, however, a major limitation is the lack of MMAM processes [114,239,210].

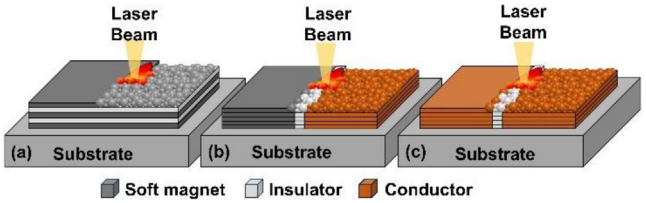

Fig. 9. Graphical representation of three multi-material bonding scenarios required to manufacture electric machinery. The multi-material LPBF process is used as an example in this case. (a) soft magnetic material-insulating material bonding for single step manufacturing of rotors and stators. (b) soft magnetic material-pure copper bonding for single step manufacturing of winding and stator. (c) Pure copper-insulating material bonding for single step manufacturing of windings.

Preliminary work on MMAM using the LPBF technique has also been done with varying levels of success. Most approaches focus on AM of a metal on a substrate made of a different metal [77,136,124]. The major shortcoming of this approach is the fact that the compositional gradient achieved at the interface cannot be controlled or augmented, a necessary requirement to achieve proper bonding across the material interface. More sophisticated approaches include simultaneous multi-metal processing systems with a focus on metal-metal bonding [254,252]. Little information is available on metal-ceramic bonding using multi-material LPBF [246,241]. These studies show promising preliminary results but there is no information on insulating and magnetic properties of these multi-material bonds.

The spatial resolution of multi-material placement within a component is critical for electric machines. In [162] and [108], a soft magnetic material—FeSi and 17–4PH, respectively—and a non-magnetic material, SS316L, are used to fabricate a multi-material synchronous reluctance rotors. The non-magnetic SS316L serves as a magnetic flux barrier, making its precise placement within the rotor essential for motor performance. In the case of SS316L-FeSi, a conventional LPBF system was modified to accommodate multi-material processing, resulting in poor spatial accuracy, as shown in Fig. 10a. Conversely, for SS316L-17–4PH, a dedicated multi-material LPBF system was employed, yielding improved spatial accuracy, as illustrated in Fig. 10b According to [108], the material interface zone spans approximately 420 µm. As dedicated multi-material LPBF systems become more accessible, further investigation is warranted to achieve uniform and controlled spatial accuracy in material placement and to study its effects on various performance metrics.

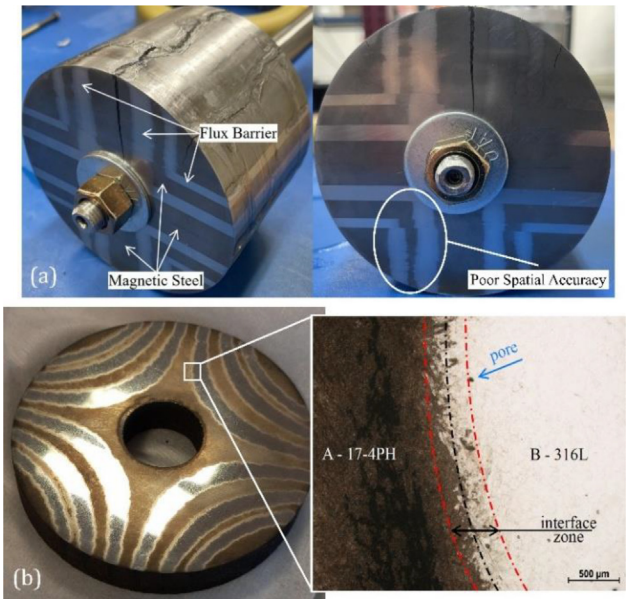

Fig. 10. Multi-material synchronous reluctance rotors manufactured via multi-material LPBF process. (a) 316L-FeSi [162], and (b) 316L-17–4PH [163].

2.5. Case study 5 – energy generation systems

AM technologies are used already widely in the field of energy generation / power plants primarily by means of DED and increasingly also by means of LPBF processes [219]. Like the other application areas explored here, the reasons for using AM processes are the improvement of component properties and especially the acceleration of development and validation cycles for new parts. In addition to this faster prototyping with greater design freedom in terms of geometry at lower development costs, the parts can be easily customized to meet specific requirements. Additional advantages for reducing power plant downtimes are the acceleration of the supply chain and delivery to the respective distributed locations in combination with production on demand, possibly even on site, and thus the elimination of large warehouses and long transportation routes as well as the faster production itself by replacing entire conventional assemblies by single AM parts. Due to the comparatively large parts for the AM process range, DED processes play a decisive role having the advantages of high assembly rates and large build volumes. In 2022, an oil company installed a printed leak repair clamp using a WAAM DED technique as proof of concept for medium-pressure steam systems [163]. LPBF processes demonstrate their advantages in terms of resolution, precision and complexity. Thus, their relevance will increase with increased capacity building chambers.

The objectives of AM use in terms of performance are usually higher mechanical characteristics, high temperature stability and high creep resistance or corrosion resistance [134]. Due to the usually extreme operating conditions, typically in terms of temperature, pressure, and corrosive environments, the production of particularly crack-free and defect-free components and the associated quality control as well as assurance are decisive factors in manufacturing. The extreme conditions also determine the materials addressed, such as typically stainless steels (e.g., 1.4404), particle-reinforced stainless steels (e.g., carbides), nickel-base superalloys, i.e., precipitation-hard-enable nickel-chromium alloy with additions of niobium, molybdenum, aluminum and titanium (e.g., 2.4668), zirconium alloys or high-entropy alloys (e.g., AlCoCrFeNi [247]).

Exemplary AM parts in the energy sector include components for gas turbines [162] (recalling dual purpose of aerospace propulsion and energy generation) such as compressor blades or fuel burners, fuel swirlers and sealing segments [31], *see* also earlier in Section 2 regarding the related application for aeroengine components, nozzle components or complete nozzles (e.g., for borehole cleaning [138]), heat exchangers [120], other fluid-carrying devices with internal channels [193], valve components [62] and various reactor internals [219,96,227] etc. The safety requirements of the components and the high financial consequence in the event of damage or failure lead to high demands on quality assurance. This shows the two sides of the coin of the layer-by-layer production methods in AM: although in a negative sense the material is only created during manufacturing, so that no material parameters can be tested beforehand, in a positive sense the manufacturing process and the workpiece produced can be fully documented with the resolution of the layer thickness through process monitoring. [275] contains a current description of the status of process monitoring of AM processes.

The established DED processes include the deposition welding of coatings like laser cladding (e.g., using the aforementioned high-entropy alloys [247]), which already exhibits characteristics of MMAM. Increasingly, however, three-dimensional MMAM with entire parts made of different materials is being considered to replace expensive materials such as nickel-based superalloys in less “loaded” structure sections with stainless steel, for example. Conversely, the performance and/or service life of components can be increased by MMAM using locally more suitable or more durable materials.

The grading of properties is already being implemented [84], whereby the same base material is used, but the formation of the phases, the grain sizes and, within limits, the local composition can be influenced by varying the process parameters in conjunction with the heat dissipation conditions; this is possible in both the DED and LPBF processes, *see* Section 4. Graded material composition, including the occasional targeted addition of carbide particles, for example, is already no obstacle and readily undertaken in DED processes, as the powder flow from various powder containers to the process zone can be specifically controlled. Beyond this graded property manipulation, however, the potential for volumetric three-dimensional MMAM is great, as extreme conditions in terms of pressure, temperature, radioactive radiation exposure, etc. require locally specific material deposition. Materials for these extreme operating conditions are more expensive, so their volume should be minimized as far as possible in terms of cost.

Fig. 4b demonstrated an exemplary use case by *MAN Energy Solutions SE / Fraunhofer IGCV* [209] in the form of an injection nozzle for large bore engines, whereby a wear and heat-resistant steel was combined with a copper alloy with good thermal conductivity. The multi-material design provides for a copper core in the highly stressed area, which leads to improved temperature control in the injection nozzle and thus to improved engine performance.

Another multi-material that has been reported is a holding ring with a diameter of 1.2 m and a weight of 290 kg (*see* Fig. 11) [242]. It is a safety element that is part of a series of shut-off valves in dams. In France, around thirty of these parts are replaced every year, although it should be noted that the dimensions of the holding ring (as with many other parts) are different for each hydropower plant. Storage is therefore extremely challenging, complex and expensive. The delivery of such a part via the conventional supply chain can take between 10 and 12 weeks. A power plant shutdown costs EDF France (Électricité de France SA) several hundred thousand euros per day.

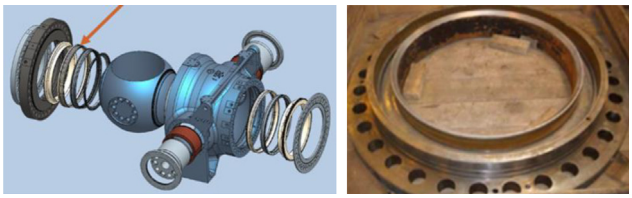

Fig. 11. MMAM use-case of EDF France in the form of a holding ring (right) as a typical spare part for cut-off valves (left) of hydraulic dams [176].

This is the motivation to manufacture such components additively on demand in future; the aim is to achieve a delivery time of 4 weeks. As a MMAM variant, the structural base should be made of high-strength steel, the areas in contact with water should be made of stainless steel and the sealing contact areas should be made of a copper-aluminum alloy.

Considering the example of the holding ring, there is great potential in the area of parts with large dimensions in two axes. LPBF machines for large but flat MMAM parts could be a supplement to DED processes in the energy sector due to the significant time and cost savings of spare part printing compared to longer downtimes for conventional supply chains, and perhaps even a game changer in terms of complexity and precision. This would not necessarily require correspondingly large multi-material LPBF coater systems to begin with, as the simple 2D material change in the build direction could already represent a compelling business case in itself.

Some companies in the oil and gas sector also expect a time saving of between 75 % and 85 % in its use cases in the mono-material AM sector (e.g., impeller made of an aluminum alloy for a multi-stage high-pressure pump for liquefied natural gas) [240], which underpins the expectations for the aforementioned MMAM case with respect to shortening the time required to deliver spare parts.

Heat exchangers have great potential to be enhanced with the use of MMAM both in the field of energy generation and in the field of energy conversion and storage. MMAM-specific application requirements could also arise in the future field of nuclear fusion reactors, as ITER - International Thermonuclear Experimental Reactor, to combine geometric design freedom with the high demands imposed on the materials (see Fig. 12). AM of plasma-facing components [268] poses a particular challenge because, on the one hand, tungsten has to be printed without cracks or pores and, on the other hand, a suitable transition to Cu and CuCrZr has to be realized despite their very different properties. This task is still extremely challenging and forms the basis of much ongoing work [223,151,101].

Overall, structural components in energy generation present significant opportunities and thus challenges for MMAM. While mono-material AM has delivered some solutions this must be expanded further to have meaningful impact.

An additional area for AM applications in the energy sector can be found in the fields of hydrogen and accumulator/battery technologies for energy conversion, storage, and transportation. The reason for using AM here is usually to improve performance and, of course, the possibility of rapid prototype production in research and development. AM (primarily polymer) processes such as material extrusion, binder jetting, PBF, vat photopolymerization and inkjet printing (material jetting) are used here due to the component sizes, the required precision and microscale features as well as the materials. Electrodes [178], membrane and electrode parts [277], diffusion-inhibiting or diffusion-promoting layers, etc. are manufactured using MMAM.

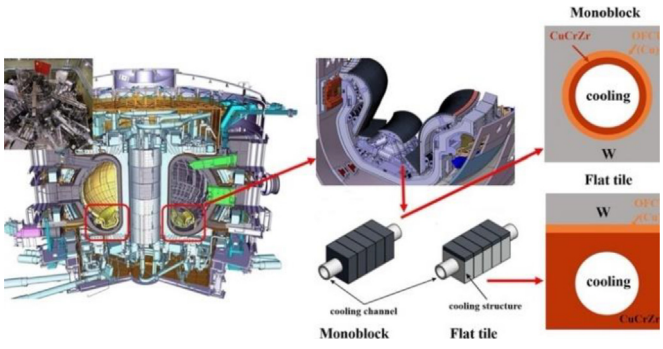

Fig. 12. Schematic illustration of ITER fusion toroid with the monoblock and flat tile structure of multi-material W-Cu-CuCrZr parts [178].

Exemplary components can be found in particular in the area of Solid Oxide Fuel Cells (SOFCs) and, to a much lesser extent, in the areas of Solid Oxide Electrolysis Cells (SOECs) and Proton Exchange Membrane/Polymer Electrolyte Membrane Fuel Cells (PEMFCs). In the case of PEMFCs, LPBF processes are used for printing titanium bipolar plate prototypes, whereby the printing of porous transport diffusion layers [143] is also considered in addition to the bipolar plate shapes and channel structures. However, SOFCs and SOECs in particular are the leading high-temperature devices for realizing a global “hydrogen economy”, but manufacturing costs, quality assurance and lifetime are major barriers to widespread use [141].

While not entirely metal MMAM, SOFCs and SOECs are complex multi-material and multi-layered systems with micro-scale elements whose manufacture usually involves dozens of individual process steps. These electrochemical devices essentially consist of an electrolyte (ceramic, typically Yttria-Stabilized Zirconia (YSZ)) and two electrodes (anode and cathode made of ceramic-metal composites (cermets), typically nickel-YSZ) plus connecting elements and sealing materials, whereby the microstructure and, to a certain extent, the thickness of the functional materials largely determine the performance of the device [37].

Similar opportunities exist with lithium-ion accumulators or batteries consisting of repeating layers of materials such as copper, aluminum, specific anode and cathode materials, binders, conductors, solvents, electrolytes and separators. An interesting approach to MMAM in batteries is to avoid the need for copper and aluminum foils [219] to allow completely printed systems. For this, so-called “free-standing” electrodes [89] must be printed [109]. Various AM processes and material systems could be considered for this purpose.

3. The governing principles of metal MMAM

It is useful to consider the physics of MMAM processes such that the limits (and opportunities) can be parameterised. Process physics is specific to the process in question, and this is explored in this section.

3.1. Resolution

Similar to any other manufacturing process the resolution at which features can be created is of prime importance. This is complicated in metal MMAM where multiple materials are deposited within a part volume. Factors such as material miscibility, interlayer adhesion, and the ability to switch between materials in-situ all impact the resolution, as well as the quality of the final product. In terms of materials processing and handling hardware, for most MMAM techniques the resolution is determined mostly independently of a single or multi-material strategy. However, for multi-material fabrication there are additional considerations. Achieving high resolution can be more challenging due to the need to precisely control the materials’ deposition and to ensure proper mixing or bonding between them. Depending on the method of material deposition different levels of accuracy have been reported in literature.

For LPBF, the resolution is determined by the optical system (i.e., laser unit, scanning head, laser spot size) on the one hand. On the other hand, the selected layer thickness is a major and well-known trade-off between productivity and resolution. Next to pre-alloying powder feedstock and continuing similar to single-material fabrication [155], generalized techniques for multi-material LPBF are sequential recoating [159], nozzle-based [67] or masking [56]. Material feedstock, albeit for single-material or multi-material deposition, is characterized by the Particle Size Distribution (PSD). For metal LPBF, the PSD

typically ranges between 5 and 50 µm in diameter. E.g., pre-alloyed nickel-titanium multi-material feedstock with a 15–45 µm fraction can be used for the fabrication of superelastic endodontic files [33]. Resulting feature sizes – in this case a 54 µm wall thickness in line with the laser spot size – are also similar to single-material builds. For a 1D transition in the build direction, by sequential recoating, the resolution is defined by the deposited layer thickness. However, the resulting resolution on component level can better be formulated as the size of the material transition zone, which for an instant material transition is typically related to the melt pool depth. Oel et al. [169] observed a transition zone of 100 µm between copper alloy CuCr1Zr and SS316L. Similarly, Wits et al. [260] also observed a 100 µm transition zone between IN718 and SS316L, and vice versa, which was directly related to the melt pool depths between both materials. For a 3D transition, also the resolution of the in-plane selective material deposition plays a role. Using a nozzle-based approach, Girnth et al. [67] demonstrated a minimum track width of 1.3 mm to deposit a single type of material, which relative to the deposited layer thickness of 100 µm can be considered quite coarse. The main challenge in this case is either in the ability to only locally deposit powder using a nozzle feeder, or locally remove powder using a nozzle-based suction system. This can be avoided using a masked-based approach, e.g., using rotating drums. The Aerosint recoater is advertised with a 300 µm lateral powder pixel resolution [88]; however, Schneck et al. [204] reported a minimum deposition track width of 0.8 mm. While there is much research attention of MMAM, the maturity levels of these concepts are relatively low. Hence, one may anticipate a higher resolution in the future. Looking at single-material LPBF, Fu et al. [55] distinguishes between conventional LPBF and micro LPBF in which the laser spot size is refined to 25 µm and below, powder particle sizes are below 25 µm and the layer thickness is below 10 µm. It is very likely that also for multi-materials this trend continues and future micro MMAM capabilities will appear.

For DED, as material is continuously being fed into the melt pool, the resolution is primarily determined by the process itself independent of the material selection. For multi-material processing, there are two principles strategies [14]. Either the material is pre-alloyed and processed like a single-material build, or material is blended in-situ by feeding various materials from multiple sources into the melt pool directly. The multi-material composition in this case is determined on the fly. Flow instabilities during the switching of feeding lines has an influence on the material composition; e.g., for Mo-Nb-Ta-W high-entropy alloys the accuracy in material compositions was between ±5 at. % and ±10 at. % [149]. Reported resolution of fabricated parts ranges from 100–500 µm [14,35] and is similar to single-material builds. Cracking and intermetallics are the most significant barriers for multi-material structures, although these challenges are similar to single-material DED [49]. For wire-based DED, Treutlet et al. [233] were able to fabricate Mn4Ni1.5CrMo tracks next to FeNi36 tracks. The resolution of a Mn4Ni1.5CrMo single track was about 3 mm in width and 3 mm in height within the FeNi36 matrix.

Using drop-on-demand techniques, such as metal jetting, the resolution is mainly dependent on the size of the droplet's equilibrium phase [66] and the applied printing strategy [160]. Resulting feature sizes of single droplets are in the order of tens of microns. Due to the deposition accuracy, the track width will show a wider value. Hereto, Nelson-Dummet et al. [160] devised a strategy to enhance the positional accuracy of single droplets and thereby increases the resolution of the printed design down to the micrometre level for a droplet size of 50 µm.

MMAM has also been reported using Laminated Object Manufacturing (LOM): different materials in sheet form can be stacked and processed. By ultrasonic consolidation sheets of different material may be bonded. The 3D-form factor is limited; however the resolution approximates the gauge of the individual sheets [158].

3.2. Material miscibility

In MMAM, three-dimensional structures are to be produced from several materials and/or with varying material compositions (different alloy element contents up to graded alloy compositions) in order to adapt the properties locally to the local and global requirements. While a compromise must be found for a mono-material AM part or a priority must be followed on the material selection, local and global potentials should be exploited in the case of a MMAM part, i.e., a titanium-aluminum-MMAM part can, for example, be particularly corrosion-resistant locally made of a titanium alloy, while it should be particularly light and as cost-effective as possible globally made of an aluminum alloy (see also the various examples in the case studies chapters with a wide range of interesting material combinations). Depending on the application, an infinite number of combinations are conceivable if the manufacturing technology (machine concept, system technology, process, etc.) allows it. The decisive factor that distinguishes MMAM from mono-material AM in terms of feasibility is the generation and the resulting properties of the interfaces or interface layers being formed, as well as the adjacent affected or transition zones to the pure mono-material sections. There are parallels here to classic heterogenous welding or thermal joining of dissimilar joints.

MMAM offers significant advantages beyond the classic benefits of AM, such as geometric freedom and design complexity. It can enhance part performance while reducing costs through strategic material combination—for example, by using expensive materials only where necessary and leveraging benefits in the printing or post-processing stages [183]. Additionally, MMAM has the potential to lower a product's environmental impact both during production (by optimizing resource consumption through a tailored material mix) and throughout its use phase (e.g., via improved light weighting, enhanced functionality, integrated features, or extended service life). However, the material combinations in MMAM parts present a challenge to achieving a circular economy, as end-of-life recycling requires material separation [85]. This issue is explored in detail in Section 5.4.

The potentials of MMAM are as diverse as the potential material combinations, with material miscibility representing a minor or major challenge depending on the combination. In the simplest case with two material sections for example of at least one metal A involved, the consideration in the MMAM ranges from [176] metal A1/metal A2 MMAM with varying alloy element contents or alloy compositions 1 and 2 (jumping or graded) via [181] metal A/metal B MMAM with two completely different metals A and B to [182] metal A/polymer A and [262] metal A/ceramic A, so that these corresponding transitions also need to be mastered in the future. Corresponding variants are of course also possible without the involvement of a metal in the area of polymers or ceramics or their combination. Of course, the more materials used in a MMAM part, the greater the potential to further improve its performance at the expense of process complexity.

As with many aspects of MMAM, when it comes to material miscibility, it is worth considering classical welding or, in general, joining processes for dissimilar joints. Processes for such multi-material (dissimilar) joints can basically be grouped into four categories (according to Martinsen et al. [190]). A distinction is made between mechanical, chemical, thermal and hybrid joining processes. Depending on the process, force is transferred by means of material bonding, form and/or force locking.

In thermal joining processes, thermal energy is used to create the joint, for example by means of electric arcs [114], laser [239] or electron beams [187], friction [97], electromagnetic resistance [98], ultrasonic vibrations [115], diffusion processes [61], pressure sintering in current flow (spark plasma sintering) [36] or explosion processes [265] (exemplary references given are for the aforementioned titanium-aluminum combination).

Actual material miscibility exists only for weldable metal-metal combinations that allow direct alloy formation and a weld metal with qualitatively sufficient properties. However, it is obvious that the greatest potential for increasing part performance often lies in the combination of extremely different material properties and thus materials for the most effective adaptation to local requirements, so that material pairings that are not suitable for classic welding are often of high interest, as in the example of titanium-aluminum.

The thermal joining of such metal pairings is often accompanied by the formation of intermetallic phases in the interface. However,

these intermetallic compounds are typically brittle. Especially the mixing of the material melts usually leads to a strong, often critical extent of such intermetallic phase formation resulting in complete interface failure [154]. Residual stresses are often induced during cooling by different thermal expansion coefficients which can further serve to undermine integrity.

Katayama's application-oriented article, which also dealt with the titanium-aluminum combinations as well as with steel-aluminum (e.g., [125]), is called "The unweldable" (translated from German) [230], as no suitable joints can be produced by conventional welding. If the material miscibility is so restricted, the established process approach for fusion joining is that only the material with the lower melting temperature is molten, while the material with the higher melting temperature remains in a solid state and is therefore more likely to be brazed. This often reduces the formation of intermetallic phases sufficiently down to thin interfacial compound layers to produce highly loadable transitions.

For AM, the first three energy sources mentioned above (laser beam, electric arc and electron beam) are established for weldable metal combinations. Due to the targeted combination of different base powder materials through combination of initial powder streams, DED processes allow the graded or abrupt change of the alloy composition in a simple way, so that transitions between two material sections can also be designed in a targeted manner. The combination of two weldable materials has generally been known for decades in the case of cladding with the aim of coating a base material with another functional coating material. This entire range of cladding processes can be applied directly to DED AM processes. One essential hurdle must be considered here, as the influences of reheating by the many subsequent layers must be considered in MMAM using DED. For example, a martensitic microstructure that is present after the single-layer deposition would no longer be present in the final part due to subsequent tempering as a result of the following layer build-up. In the aforementioned example of titanium-aluminum and other combinations with the formation of intermetallic phases along the interface, the heat input of the subsequent layers must also be taken into account, as this can lead to further intermetallic formation.

In LPBF processes, different materials can be combined vertically in the build (z) direction and laterally in the build plane (x-y) in accordance with the system technology options. In the case of weldable material pairings or alloys, vertical build-up is only limited by the possibilities for changing the powder (and, in terms of costs and resources, by the effort involved in recycling the powder that has not been molten). Obviously, there is also the challenge that process parameters may have to be adapted for the transition, i.e., the first layer(s) of the new material [60]. However, this vertical case is generally comparable to the 2D hybrid production of AM part segments on conventionally manufactured components or semi-finished products.

MMAM is more complex in the case of LPBF for lateral multi-material design (*see* Fig. 2). Powders of different weldability materials/alloys can already be deposited laterally (at least with reduced geometric voxel resolution) in the powder bed using multi-powder coating systems, *see* Section 4.3. Depending on how precisely the systems can place the two powder types next to each other and how much unwanted cross-contamination occurs, a wide variety of actual powder mixtures must be molten here, due to the relatively small laser beam spot diameter and resulting melt pool sizes in case of LPBF. Thus, at the transition between the different powder types, the process parameters must be interpolated between material A and material B or robust enough to be suitable for both materials and different mixture compositions. Monitoring the composition at the laser beam position, for example, would be one way of making this barrier more manageable and controllable.

In the case of low or no material miscibility, such as the formation of intermetallic phases described above, both vertical and lateral transitions in the powder bed are particularly challenging and still represent a major barrier. The approaches described from the joining of dissimilar compounds are not directly transferable to MMAM using LPBF, for example for titanium-aluminum [60]. LPBF-specific limitations (transmission of laser radiation through the powder layers) and LPBF-specific potentials (extremely small melt pools and high cooling rates) are evident here, so that unforeseen solutions can also arise in addition to challenges. In [60], for example, initial tests show that the direct build-up with titanium powder on aluminum substrates in the LPBF process is not impossible and offers potential, even if development is still needed to be able to manufacture both dense mono-material sections with a high-strength interface at the same time.

Again, also with a view to thermal joining, it should not go unmentioned that the use of bridging materials as intermediate layers can also be used in MMAM. For example, in the case of Ti6Al4V-SS316 as multi-metallic combination a new material route Ti6Al4V → V → Cr → Fe → SS316 was successfully fabricated by laser 3D printing to avoid the formation of intermetallic Ti-Fe phases [235].

In the wider field of MMAM, polymer-polymer, polymer-metal or polymer-ceramic variants can also be joined chemically at the interfaces or transitions in the form of co-curing or co-sintering. A joint is chemically joined, if a chemical reaction was responsible for this. Bonding is therefore referred to as a chemical joining process, whereby the force transmission is determined by the adhesion of the adhesive to the joining partners and by the cohesion within the adhesive. Mechanisms of mechanical joining processes such as micro- or nano-interlocking (e.g., improved adhesion at titanium surfaces via laser-induced surface oxidation and roughening [167]) can also play a role in the polymer-metal interface, so that pure adhesion or material bonding is supplemented by interlocking effects with form and force locking.

Overall, the complexity and challenge of MMAM increases in the case of metals with decreasing material miscibility. Material pairings where constant process parameters can be used, to pairings where the process parameters of a mono-material section can also be used in the transition area, and pairings where the parameters must be interpolated, to pairings where the formation of critical intermetallic phases or the need of intermediate layers must be considered.

3.3. Energy delivery considerations

One key challenge in generating multi-material parts is the adequate energy supply to melt the underlying raw material. The energy input can be tailored on different levels while each of these levels affect the quality of the final workpiece. With a commercially established AM machine that is equipped with a specific laser source, the next logical step is to add means to tailor the process dynamics during processing. Available system technologies for this range from diffractive optical elements over spatial light modulators to laser sources with integrated options for modifying the intensity distribution within the laser spot. In processes such as LPBF and DED, the latter technology is often used since it provides a low complexity solution that can support the use of different beam profiles.

By tailoring the process dynamics, mixing effects at the interface between two materials can be manipulated to either decrease or increase the size of the dilution zone. Adjusting the size of the mixing region can help to overcome solubility limitations and to counter the formation of undesired brittle phases by avoiding e.g., element agglomeration and segregation. Linked to this is the control of the temperature fields within the workpiece by adjusting the intensity distribution during processing. Specific part regions could be pre-heated (or post heated) during processing to alter the thermal gradients. Correspondingly, the stress formation and thus the crack tendency in critical regions can be affected to improve the processability. Another potential of applied beam shaping is the reduction of spatter formation in the interaction zone. Rothfelder et al. [211] transferred these finding to first investigations in the field of multi-material manufacturing. By selecting elemental tungsten as tracer particles, it was possible to determine the influence of different intensity distributions on the cross-contamination. It was found that the effective cross-contamination could be significantly reduced by applying beam shaping. This finding is elemental for the later

generation of multi-material parts since an uncontrolled spatter formation would result in non-predictable material properties.

The approach for adjusting the energy input is to address the energy source that is used for melting the materials. In laser-material processing, the absorption coefficient of the underlying material decisively affects the energy coupling into the workpiece. Copper, which is highly relevant for industrial applications due to its excellent thermal and electrical conductivity, is characterized by a poor laser energy absorption in the near-infrared range. The absorption coefficient depends strongly on the selected wavelength and generally increases for shorter wavelengths. Correspondingly, laser sources such as green ($\lambda \approx 515$ nm) or blue ($\lambda \approx 455$ nm) lasers can be used to improve the energy coupling into industrially relevant materials such as copper. Selecting the laser source based on the underlying material helps to improve the process stability. The better absorptivity of e.g., copper allows for a better control of the energy input into the workpiece when selecting blue or green laser sources. However, a penalty associated with the change of the laser source is typically a poorer focusability of the laser beam due to a reduced quality of the laser beam. While these effects might not be critical due to large laser spot sizes that are applied in DED, the resolution of parts manufactured via LPBF will be affected. Another limitation is the altered energy coupling into materials that have already been thoroughly investigated for Near-InfraRed (NIR) laser sources. As for copper, the absorption coefficient is also influenced by the wavelength for other materials such as iron-based alloys. It is therefore necessary to develop an adequate process understanding on the influence of the laser source on the laser-material-interaction.

An alternative to a complete change of the laser source can be the selection of dual-lasers. These systems irradiate at different wavelengths and allow a flexible change of the laser irradiation. Correspondingly, different regions within the part can be illuminated with the laser system that is most suited for the respective material to achieve the best result. The main disadvantage is the discontinuous use of both laser wavelengths. The off time of the second laser leads to unnecessary investment costs, which only further inflate the average costs per part. Beneficiary in contrast to dual-laser systems is the use of multiple single lasers by either guiding those laser sources via the same processing optics or by simultaneously illuminating different part regions. In the latter case, the average time per part and thus the production costs can be reduced significantly.

The simultaneous use of two laser systems further allows for the use of one laser as e.g., a preheating unit while the second laser is used for applying the energy delta to melt the material. Here, the combination of the laser systems (same or different operating wavelength) could be adjusted based on the targeted application. For example, a NIR and a green laser source could be used for the generation of multi-material parts from copper and steel. Therefore, the NIR laser is used for manufacturing the steel regions while the green laser is used for a better energy coupling into copper. One key advantage of these simultaneous strategies is that internal stresses can be met by adjusting the temperature profile. Adjusted temperature profiles are again desirable to reduce e.g., crack formation in crack-susceptible materials.

Another potential for multi-laser processing in multi-materials applications could be identified by using both continuously emitting (continuous wave (CW)) lasers and Ultra-Short Pulsed (USP) laser systems. The high precision of USP lasers, due to high pulse energies, supports the generation of highly resolved geometries within the parts. These structures can be generated either by a spatially resolved melting of the underlying (powder) material or by ablating material from the surface of the workpiece. Consequently, it is possible to manufacture parts with feature sizes that fall below the ones that are currently realisable using established system technology. The main challenge is that USP laser systems have barely been used for AM processes. Correspondingly, the available understanding on the laser-material-interaction in a continuous build process is limited.

An underestimated lever for producing multi-material components is the use of high-temperature platform heating units. In multi-material processing, the bonding zone between two materials is highly critical and defect formation is predominantly found in this area. Defects like cracks can form due to too high temperature gradients. Preheating the dilution zone provides an additional lever for tailoring the temperature gradients within this region. Correspondingly, it is possible to skip temperature ranges in which undesired effects like, e.g., crack formation would be promoted. One possibility is to heat the substrate or workpiece to temperatures close to the melting point of the lower-melting material. This approach allows a precise control about the internal thermal stresses. However, high-temperature preheating units are limited to temperatures of around 1200 °C. While these temperatures are sufficiently high for aluminium, titanium, copper and most of its alloys, a delta remains for other relevant iron-, cobalt-, or nickel-based alloys. The highest potential can therefore be identified when generating gradients between low- and low-melting as well as between low- and high-melting materials. Nevertheless, high-temperature heating still provides an important technique to reduce the thermal gradients when generating multi-material parts based on two (or more) high-melting materials.

4. Machinery, apparatus and allied capability

As interest in MMAM grows, there are a number of innovators and machine makers seeking to capitalize on this capability. As discussed in Section 2 several industries stand to benefit from advances in MMAM and as such the rate of capability development is staggering. To date the machine types explored build heavily upon DED and LPBF platforms but other capabilities are also emergent. These are explored in this section.

4.1. Directed energy deposition

DED presents as an outstanding candidate for metal MMAM. Since material provision to the fusion zone is usually delivered continuously and through independently controllable feeding units (wire and powder being the most common forms), it is possible to adjust material feedstock in process as part of a given machine cycle. This has been capitalized upon by a number of machine makers including Optomec and Formalloy. Here, up to 16 powder feeders can be called upon to feed variable amounts or ratios of different materials towards the build chamber and ultimately enter the fusion zone. In addition to material being delivered sequentially, partial fractions of materials can be delivered concurrently to allow blending within a manifold. This allows the designer to specify a combination of materials for a given coordinate within a part (*see* Fig. 13).

Similar capabilities are available from several providers and numerous laboratories have built apparatus with similar characteristics. Perhaps the earliest works can be attribute to Lewis' group firstly for "direct light fabrication" with single materials [229] and followed

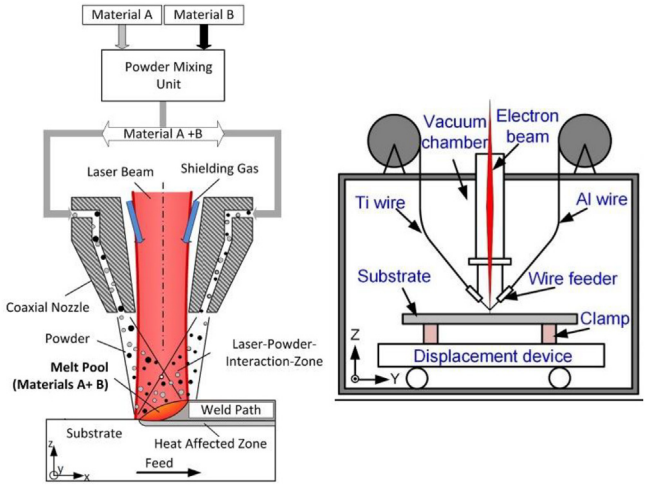

Fig. 13. DED apparatus capable of MMAM is now readily available with both powder and wire as feedstock. The powder feedstock example is provided by Muller et al. [207], and the wire feedstock process is provided by Xu et al.

up with multiple materials in their excellent work which offers a practical guide [117]. The origins of this technology may trace their roots back to both laser cladding [131] and weld overlay where multiple materials have been applied to provide surface enhancement or indeed repair. The enabling technology to allow exploration of 3D manufacture relates to the development of superior CAD/CAM systems and enhanced machine architectures.

The principle energy delivery modalities for DED (laser, arc and electron beam) have all been subject to some exploration of MMAM with varying success. Unlike powder bed approaches the process creates some significant constraints and resolution is hampered by typical track widths which are typically 5–10 mm. While resolution and design freedoms may be lacking, deposition rates in DED can be as high as 1000 cm^3/h [121], which underscores the productivity expected from these approaches in the future.

Given the relative coarse nature of DED deposits significant effort is now being poured into machining to deliver the net geometry and material condition sought by designers. Factors such as residual stress [273] in complex scenarios must be overcome in order to deliver useable parts.

The DED platform technology continues to develop at a staggering pace and the technology continues to become more affordable as cost/kW of lasers continues to fall as new makers enter the market. In addition, the capability of WAAM continues to compel users primarily interested in steel(s) deposition to invest.

4.2. Material extrusion methods

Material extrusion methods in AM entail methods like Material/Metal Extrusion (ME), Fused Filament Fabrication (FFF) or FDM, the latter of which was introduced as a brand name. It is an additive process in which the functionality and important components of the systems can be deduced from the names mentioned. The starting materials are usually polymers but extrusion of metal pastes (e.g., Rapidia metal extrusion) lends itself well to metal MMAM. These are called wires or, in the plastics sector, filaments. These precursor materials are heated in extrusion chambers so that the viscosity decreases sufficiently and then pressed through a nozzle. The diameters of the nozzle openings are usually smaller than one millimeter to increase the resolution. In addition to the nozzle opening, the layer height, which is influenced by the pressure, the flowability (and wettability), and the traversing speed, determines the geometric resolution. The thinner the layer, the lower the step effect of the printed geometry. The thicker the layer, the greater the build-up rate. The surface quality is rather rough compared to other polymer AM processes such as stereolithography, with clearly recognizable layers. Mechanical and/or chemical post-processing is required for better surfaces.

In contrast to the many DED and LPBF processes, no laser beam, arc or electron beam is used here, which is a major reason for the low entry-level prices of the printers. The low entry-level prices have also made it an established AM process for home users. However, there are also machines for industrial production. The range of materials that can be used is just as broad as the range of machines. It goes from inexpensive materials such as PolyLactic Acid (PLA) with comparatively low mechanical properties to high-performance polymers such as PolyEtherEtherKetone (PEEK), though this requires correspondingly more expensive machines. In principle, the required processing temperature increases with the mechanical performance. Additives such as short fibers can be added to the filament to further increase the mechanical properties. Corresponding filaments are available with carbon short fibers, among others. The machines become more complex if long carbon fibers are to be introduced [166]. In addition to reinforcing fibers, additives such as iron or steel particles can also be integrated into the filaments, for example to create magnetic properties [43]. While this technology has only had modest impact on metals AM, there is some advantage in considering it as the most widely used approach to MMAM.

As with the wire-based DED processes, 100 % material utilization is characteristic of this material extrusion process class. As with the wire processes, changing the material is also comparatively simple, as no powder residues need to be removed. It is sufficient to change the filament and possibly the extruder head or nozzle in the case of contamination. The geometric resolution is higher than with the metallic DED processes (particularly due to the typically low layer height of a few tenths of a millimeter down to approximately one tenth of a millimeter), but higher than with the LPBF processes, which use even lower layer heights and track widths. The minimum wall thickness that can be produced is typically in the order of a millimeter.

Areas of application for polymer components include model making, prototype production, spare parts production on demand, custom-made products and fixture construction.

Support structures are generally used in the processes depending on the geometry to be printed. A distinction is made between soluble and mechanically removable support structures. In order to deposit the support structure material and the actual print material for the part, most devices have at least two print heads or two extruder and nozzles. Additional heads can be added to process other materials in accordance with MMAM. The first step towards MMAM in this process group was the printing of differently colored variants of the same material for design reasons. Increasingly, however, different polymers are also being combined, whereby different print heads are always used, as different process parameters are required on the one hand and to prevent cross-contamination in the sections on the other hand.

The properties of the part depend heavily on the base material selected. It should be emphasized that the mechanical properties are often clearly anisotropic, as the adhesion between the layers is generally lower than the strength within the bead and therefore within the layer: see adhesion mechanism discussion in [53]. Typical defects that can occur are slippage of the part during the layer-by-layer build process, delamination between layers, stringing between geometry features or warping causing detachment from the build platform. Porosity can be a defect or a feature, as with other AM processes.

In addition to multi-nozzle devices, for example with five heads [6], some further concepts have been implemented to realize MMAM with different polymers. Espalin et al. [47] used a mobile platform between two printers. Khondoker et al. [105] used an extruder with two inlets for two filaments into a mixing chamber. Ren et al. [189] developed a system with active mixing for gradient 3D printing and Roach et al. [58] combined the fused filament process with other polymer AM processes using robotics [98]. The overview paper by Garcia-Collada provides a broader overview about the state of the art and advances in polymers based MMAM.

Significantly larger barriers can be found when moving from the pure polymer-polymer MMAM approaches to the polymer-metal MMAM aspect, which would have great potential for certain applications. However, the systems considered here do not allow direct processing of metals, as the corresponding temperatures cannot be reached. However, it is possible to produce and process filaments with a metal content, as mentioned above for magnetization. In this process, small metal powder particles are embedded in a polymer binder to produce so-called metal filaments. The metal content can be dominant, see e.g., 85 % in [256]. As with binder jetting in a powder bed, these metal filaments can then be used to print green parts. In order to obtain a metal component with a high density, these green compacts must be subsequently debinded and sintered at high temperatures, whereby strong shrinkage occurs, while the binder content disappears. However, the high sintering temperatures also logically prevent actual metal-polymer MMAM parts from being manufactured directly using this process class. The pure polymer section would be destroyed by the sintering process. The process class described here can therefore only be used in combination with other AM process types for the production of metal-polymer parts, e.g., a combination with electroforming [130]. However, these are only very initial approaches and not established concepts.

It is of course possible to subsequently build up a polymer part section on a metal section that has already been manufactured or sintered using a different process. However, the challenge here is to

create a sound bond. In addition to adhesion, interlocking mechanisms from the macro to the micro and nano scale play a role here. Rough surfaces or open porosity in the metal part surface can have a direct benefit here. Whether such surface features contribute to interlocking and thus to bonding naturally depends on the surface tension, viscosity, flowability and wettability of the fused polymer and thus on the material combination and the process parameters applied.

4.3. Powder bed fabrication techniques

Unlike DED and fused deposition methods, powder bed techniques do not easily lend themselves to multi-material capabilities. However, as the most widely adopted technique in industry, powder bed methods stand to benefit significantly from the implementation of multi-material capabilities. Before this transition can occur, three primary challenges must be addressed. In this section, we will introduce these barriers and highlight early efforts by the research community and private companies to overcome them.

The first barrier to implementation is the need for capable powder deposition apparatus. For commercial viability, this new apparatus must maintain the same resolution as its single-material counterpart—essentially matching the diameter of the electron or laser beam. Additionally, it should not significantly prolong the manufacturing process or cause material cross-contamination.

Conventional powder bed techniques use a blade or roller to spread a thin layer of powder across the build area. New developments have introduced contactless designs, where gravity-assisted deposition spreads the powder. However, selectively placing multiple powders across the build area requires a different approach.

Numerous attempts have been made to explore alternative powder spreading methods to enable multi-material deposition. A schematic of the most common multi-material powder deposition techniques is presented in Fig. 14. Vibration-assisted capillary nozzles is the most studied technique. Inspired by the ancient art of sand painting, this technique was first explored in the context of MMAM by Pegna et al. [175] in 1999, where they demonstrated controlled deposition of various powder materials. The approach was revisited in 2014 by Stichel et al. [218] and Chianrabutra et al. [34], who further developed controls for mass flow rate and layer thickness.

Despite these early efforts, vibratory nozzles were not integrated into any powder bed system until 2018, when Wei et al. [252,281,249,250] published a series of studies demonstrating bulk multi-material samples fabricated using ultrasonic vibration-assisted nozzle dispensing (*see* Fig. 14b). While this method achieves promising deposition resolution, a single multi-material layer deposition can take several minutes to complete, depending on the size of the build area, compared to the mere seconds required for single-material layer deposition with blade or roller. As a result, despite its potential, this method faces significant challenges for industrial adoption due to its low deposition rate.

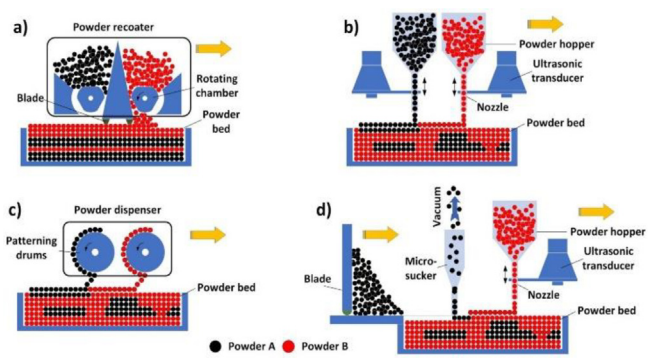

Fig. 14. Various methods for selective delivery of multi-material powder in LPBF [14]. Theoretically all of these are compatible with both laser and electron beam means of fusion.

Another popular approach leverages the conventional blade or roller recoating mechanism. After material A is deposited and solidified, any unsolidified material A is removed from the build area using a precisely controlled vacuum head. Material B is then deposited into the vacant space using a separate recoating mechanism and subsequently solidified, resulting in a multi-material layer. A variation of this technique is depicted in Fig. 14d This method was first introduced by Chivel [35] in 2016 and has since been further explored and demonstrated by others [15,10,23]. While micrographs and chemical composition analysis confirm proper bonding, the bond strength between the materials has not been determined. More rigorous work is required to further validate this technique. The multi-material deposition resolution for this method is essentially limited only by the laser beam diameter, which makes it superior to the vibration-assisted nozzle method in terms of precision. However, the deposition rate is significantly longer than that of a single-material recoating process. Given that slow processing times have always been a major pain point for the industry, this method is likely to face significant challenges in terms of adoption and commercialization. An exemplar implementation (Aconity) alongside exemplar parts can be seen in Fig. 15.

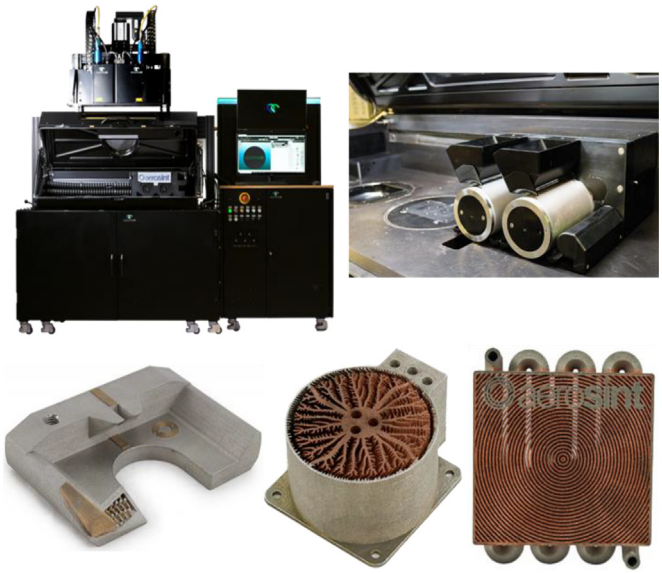

Fig. 15. The commercially available multi-material LPBF system by Aconity 3D GmbH with integrated selective powder deposition (SPD) module developed by Aerosint Schaeffler SA. (Examples of multi-material parts courtesy of Aerosint.com).

As of the time of writing, only one commercially available solution exists for the multi-material powder deposition challenge. Developed by Schaeffler Aerosint SA, the Selective Powder Deposition (SPD) module uses several rotating drums (each supplying a different powder material) to deposit material onto the build area. Powder deposition is controlled by vacuum suction valves through numerous pipes within each drum [82]. A more recent version of the SPD module uses piezo actuators to control the powder delivery through each individual pipe. The SPD module is normally provided with two or three drums to deposit up to three different materials at speeds of up to 50 mm/s, covering a 300×300 mm area with a lateral powder pixel resolution of 300 µm. This makes it the most compelling solution available today.

Early efforts in utilizing the SPD module show satisfactory metallurgical bonding between the dissimilar materials and orientation dependency of interfacial bond width and quality with respect to recoating direction [118,119,42]. Preliminary results suggest the need for further research in improving deposition accuracy, laser-powder alignment and overall machine performance.

Another barrier to implementation is the lack of established guidelines for multi-material process design. In this context, process design refers to the planning and decision-making activities that

define processing parameters, materials, and workflows used to transform a digital model into a finished product. It involves human interaction with the tool, the influence of machine parameters on material properties, and the final product's integration within the broader ecosystem.

While there is an extensive body of knowledge on single-material PBF techniques that covers every aspect of process design [157,132,113,24], our understanding of multi-material process design is still in its infancy, with results gradually emerging. A critical issue is managing the material interface, also known as the transition zone. In multi-material PBF, laser or electron beam parameters must be adjusted not only based on part geometry and location but also in response to material composition. The formation of compositional gradients at the interface, mismatches in the CTE between materials, significant differences in melting temperatures, and variations in the Marangoni number all influence the parameters required for processing the interface.

For instance, Schroeder et al. [206] demonstrated that precise control of the laser beam and careful geometrical design of the interface are necessary to achieve defect-free bonding between tool steel 1.2709 (X3NiCoMoTi18−9−5) and the copper alloy CW106C (CuCr1Zr). They outlined three major process design steps: linear grading of energy input in the build direction (z-direction) over a selectable number of layers, homogenization of the transition zone within a single layer using wobbling during re-melting, and discretization of inclined transition zones through specific increments to combine the first two steps. A more holistic approach to multi-material process design was presented by Meyer et al. [139], who proposed a series of material-specific and process-specific design guidelines to increase the likelihood of successful multi-material prints. They concluded that multi-material LPBF is an anisotropic process where material arrangement significantly influences interfacial characteristics.

With the advent of multi-material LPBF systems, a surge of similar studies on process design is anticipated. This presents a prime opportunity to explore a range of topics, including quality control, process optimization, characterization, testing, and scalability to name a few. However, the authors believe it will take several years before the findings of these studies are fully codified into process design and seamlessly integrated into the multi-material AM workflow. Industry adoption is unlikely to occur until this integration is complete.

Other approaches such as electrophotographic powder application [51] and electrostatic powder attraction [50] are currently being investigated. Readers are referred to Mussatto's work on state-of-the-art multi-material deposition techniques for a more in depth review of these systems [155].

The final barrier to the implementation of multi-material PBF is powder cross-contamination. Regardless of the deposition method used, some level of cross-contamination is almost inevitable. It is highly unlikely that any multi-material powder deposition apparatus can be designed to guarantee zero cross-contamination. Even trace amounts of cross-contamination between powders can result in undesirable phase formations, compromised mechanical properties, or defects at the material interfaces, all of which can undermine the integrity and performance of the final component. The risk is especially pronounced during the deposition and recoating processes, where residual particles from one material can inadvertently mix with another. Such risks are unacceptable in critical industries like aerospace, where stringent process certification and part qualification guidelines demand the highest levels of precision and reliability [257]. Machine development and in particular sensor capability to detect residual particles and contamination could help to alleviate this challenge, as is discussed next.

Cross-contamination poses two challenges that offer avenues for future research. First, prevention, detection, or mitigation of cross contamination in manufactured parts. To address this challenge, future research could explore several potential solutions. One approach is the use of in-situ monitoring and feedback systems that can detect and correct cross-contamination in real-time during the manufacturing process. Additionally, research into post-processing techniques, such as selective chemical or thermal treatments, could help mitigate the effects of any cross-contamination that occurs during fabrication. Furthermore, simple yet effective solutions, such as shutting off the shielding gas while depositing powder will emerge as our understanding of this process matures [139].

The second challenge is the reusability of mixed powder. The remaining powder, which is typically recycled in a single-material PBF process, will require additional processing before it can be reused in a multi-material context. To address this, various separation methods—such as magnetic, density, size, or chemical-based techniques—can be employed to separate and recycle the powder after processing.

4.4. "Digital twins" for MMAM

There are several overview articles on digital twins relating to AM, but it is apparent the maturity even for mono-material AM is low. The main obstacle to creating a digital twin for a MMAM process and part is the general increase in complexity. Especially the interface (layers) and transition zones are crucial for the process behavior as well as for the final part properties.

Both process simulation and process monitoring are still largely applied to mono-material AM. Today, there are many approaches and applied concepts for process monitoring, e.g., for DED or LPBF. For example, the powder bed topography can be dimensionally monitored or the DED part geometry can be measured before and after the melt pool. Temperature fields can also be monitored in various ways and used for control purposes.

What is missing, however, is the consideration of material-specific characteristics. At the same time, this new degree of freedom in MMAM increases the range of parameters that can be varied. The need to increase efficiency in process and part development through digitalization is therefore actually increasing because of MMAM. Approaches and concepts are therefore needed to make use of the increased degrees of freedom without further increasing the experimental effort through additional trial-and-error parameter analyses.

A major hurdle for the creation of digital twins is the MMAM printing process itself, which cannot yet be simulated or monitored in a suitable manner. The performance of a MMAM part is decisively determined by the properties of the material transition. So, their prediction by simulation or their determination by process monitoring must become possible to be able to develop digital twins both for process development and for part monitoring throughout the service life. In future, material-specific aspects must be given greater consideration.

The aim of the digital twin is to digitize the entire MMAM process chain and the final part features and properties so that the design process, the manufacturing steps, the use phase and part recycling can be taken into account. For example, in order to minimize the overall conservation of resources over the entire lifespan ("cradle-to-grave") of a MMAM part through a suitable multi-material design, life cycle assessments for the production of the base materials inclusive powder recycling, the MMAM printing process, post-processing steps, usage behavior over the service life (lightweight potentials, functional improvement, wear reduction, service life increase, etc.) as well as part recycling, etc. must be implemented in the sense of a circular economy and made available in a database. These considerations seem somewhat moot at this point given the mechanical maturity of the machines currently available for MMAM.

4.5. A note on sustainability and recyclability

Due to environmental challenges and sustainable best-practices, the focus on sustainability and recyclability of materials is becoming increasingly important. It is apparent that emergent manufacturing methods should be especially cognisant of this. Sustainability of AM processes and AM material recycling have been investigated in various studies [110,81,27,266,144] that, in general, claim that metal AM has opportunity to enhance sustainable manufacturing endorsed by the ability to produce complex geometries with minimal material waste.

Peng et al. [177] consider three aspects of environmental impact in the context of sustainability of AM: economy, environment and society. They found that energy and material consumption represent the largest impact. Energy efficiency is largely correlated to component design parameters [68]; however, the specific energy usage is not related to part complexity nor the number of parts built [168]. To push sustainable aerospace part production reliably, requirements for powder reuse have been standardized [195]. The achievable material efficiency for single-material LPBF is high, up to 97 % [30,103], wasting only a fraction of raw material in the form of non-reusable powder. Moreover, including at least 30 % recycled materials in the feedstock will result in a 25 % reduction in CO_2 emissions [133], although the metallurgical feasibility of this approach is questionable.

For MMAM the reuse of feedstock material, in particular powder, is less obvious. Combining different materials with varying properties can lead to compatibility issues, making recycling more complex. Separating individual materials from a multi-material part can be difficult, increasing the risk of contamination and reducing recyclability. When utilizing SPD methods, the specific powder utilization rate is higher; however, unprocessed powder within the powder bed can still cause cross-contamination [251]. Compared to LPBF, DED, notably interesting for larger parts, tends to be more sustainable from an energy consumption perspective [148]. However, for powder-blown DED, large areas of spatter and overspray are common during part production. Direct reuse is not advisable due to the high likelihood that ejected particles are heavily oxidized despite the shielding gas; more so for multi-material processing when ejected particles will be mixed as well. Here powder recycling follows similar routes as LPBF.

For powder-based processes, Binder et al. [23] have identified separation principles based on material and powder particle properties. Most promising according to their study are: density and magnetization as material differentiator, and the size, surface and mass properties as particle differentiator. Horn et al. [86] conducted a comparative study and concluded that flotation techniques, heavy media separation, principles based on particle inertia, magnetic separation and dry sieving appeared to be most promising. Sink rates have been examined in a fluid media-based sedimentation sorting process to segregate metal AM powder mixtures [87]. Santecchia et al. [198] constructed a powder separator in which powder is fed through a permanent magnet. Herewith they separated ferrous maraging steel and non-ferrous titanium powder particles from each other. Also, tool steel (X3NiCoMoTi18−9−5) powder and copper alloy (CuCr1Zr) powder can be separated via magnetization [208]. Powder sieving [35] and screening [85] have been investigated as a methodology to restore binary metal powder mixtures of different particle size distributions to the original source and reuse them. Two-staged screening resulted in 74 % recovery of the original powder mass and powder purities up to single-digit parts per thousand foreign particles [85]. The surface structure of the powder (i.e., sphericity and roughness) affect the flowability and can hence also be used to separate powder feedstock with distinct shape and roughness properties [263].

To bring down material recycling cost, the possibility of using non-standard arbitrary shaped metal powders for DED processes has been examined [59]. Future development of efficient recycling technologies and processes for MMAM parts as well as production (powder) waste streams will be crucial for closing the recycling loop. Naturally, the space industry is a big supporter of explorative initiatives in this realm [180] given the need to maintain high material utility rate in future extraterrestrial missions.

4.6. Design and modelling tools for MMAM

Current class MMAM design tools are largely comprised of bacterizations of solutions designed for single-material approaches. Generally, AM design tools can be classified into two broad categories: i) part design and optimization and ii) build file preparation. In many cases proprietary solutions are used in original part design and optimization (e.g., Solidworks, CATIA, Fusion360, Flow3D, Ansys, nTop, etc.) however open-source solutions are also available (e.g. OpensCAD, FreeCAD, Blender, OpenFOAM, and PicoGK). In addition, build file preparation tools are provided by vendors (e.g. Materialise Magics, Dyndrite, Netfabb, etc.) which provide analysis through to machine G-Code generation. Indeed, there are opensource counterparts available as well, such as PrusaSlicer and Cura which are now widely adapted and repurposed for machine-specific applications. The opensource license allows for developers to contribute modules which enhance functionality and can be improved by subsequent developers.

The STL file continues to be the file format of choice for 3D printers for both amateur and professional despite its many limitations [112]. This format attracted and retained users due to the ease of creation and the low memory requirement for storage and transfer. Essentially an STL file comprises a list of Cartesian coordinates with an ID which allows them to be assembled into triangles with a normal direction for each triangle identified. This allows for a manifold geometry to be identified. Successors to the STL have been explored including Lipson's proposal [83] and the 3MF Consortium [1] for a data-rich format which would include voxel specific properties (readers are referred to [112] for a comprehensive list of available file formats and their ability to represent multi-material data). This presents an interesting opportunity to volumetrically identify elements and assign material property to them to be converted to machine instruction capable of producing multi-material parts. This has not been seized upon due to high level of computational design skill required to create and deploy these models. Typically, designers in current class workflows form a compound part comprised of a number of STL files intersecting. In this case each STL defines a volumetric region subject to a distinct material delivery and/or processing condition. However, in all processing scenarios the interface between adjacent processing conditions/materials is a primary concern. For metals, weldability must be a primary concern. Additionally, these multi-material geometries typically reach a level of complexity where manual placement of multiple STL files, while ensuring proper intersections, is no longer possible. Fig. 16 shows two examples of such designs. The computational geometry engine, PicoGK, used to create these designs is available as open-source [116].

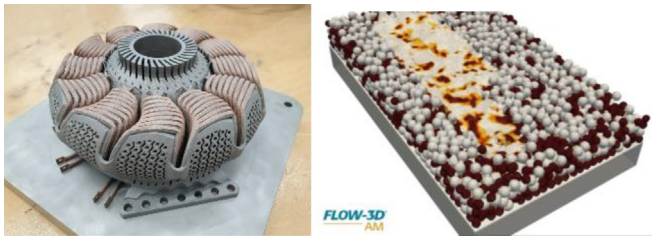

Fig. 16. (Left) PicoGK was used to create a complex prototype rotor (courtesy of LEAP 71) (Right) Flow3D amongst other tools is now being used to evaluate how multiple materials interact upon fusion in AM techniques (Courtesy of Flow3D).

Clearly new capabilities are required for the next generation of design tools. Where morphological complexity will be sought alongside MMAM, the design decisions to be made will exceed the cognitive ability of designers in the classical CAD/CAM sense. This is best exemplified by the generation of increasingly complex lattices [12] some of which require complex numerical definitions [71] or emergence of biomimetic design algorithms [72]. In addition topology optimization routines are now widely explored following contributions by Sigmund et al. [18]. Much of this design complexity deals only with single material feedstocks with precious little consideration of how MMAM will impact these approaches. However, the manufacturing capabilities explored here will require these design tools to coordinate with machine control such that understanding where materials must be placed will be driven by optimization procedures in their own right [142,8]. The success criteria for these must be a compound of part function but also process capability.

Considering the newly emerging boundary conditions of MMAM, adjusted design strategies should be implemented. Mixing two or

more materials to different degrees with one another opens almost endless new possibilities of novel compositions. Applying optimization algorithms based on a limited experimental dataset would be helpful for achieving the best result. Bayesian optimizations, which are commonly used for the development of novel materials [46] could be a powerful tool here. Furthermore, Artificial Intelligence (AI) is a powerful tool to enhance the development of novel materials [279], especially in interfacing between two materials, and reduce development times in MMAM. It is also conceivable to expand these approaches for MMAM using cluster-based structural optimization based on Bayesian methods [123]. Consequently, it could be possible to either adjust the material selection in the gradient zone, modify the size of the respective zone based on the material properties, or a combination of both. Adequate data could be provided when using the different process emissions that can already be detected in mono-material AM. These process signatures could include thermal information, detected e.g., via infrared cameras [146] or ratio pyrometers [76], and geometrical information like layer height in DED [20]. Again, AI could play an important role here since it is a powerful tool for efficiently merging the different sensor datasets [26]. In doing so, correlations between materials and processing strategies in MMAM can be identified more easily and less expensive. Nevertheless, a profound process understanding still needs to be present to assure that the resulting information from the AI data analysis is actually contributing to a knowledge gain.

Regarding product design using AI, a profound overview over the progress is provided in [248]. In this work, it is mentioned that a human-AI collaborated product design paradigm will most likely be established in the future. This assumption addresses exactly the necessary collaboration of designer or AM expert and generative AI tools. While AI is used for performing iterative tasks at high computational power, the human operator evaluates those results regarding their feasibility. Furthermore, AI can continuously be expanded based on the obtained results. Since design for MMAM is only in its infancies, additional research and development is needed in this field with regard to the boundary conditions of generative manufacturing processes.

One final important topic that needs to be considered in MMAM are post-processing operations to meet the requested dimensional accuracy, as well as standardization and qualification processes. Standardization activities are currently ongoing to establish the boundary conditions for the use of AM components in industry [248,102]. As if this was not challenging enough for mono-material parts due to e.g., anisotropic part properties, MMAM opens completely new dimensions with regard to material properties. Consequently, the potentials and limitations of MMAM need to be considered in future standardization activities to promote the use and growth of AM. Associated with the standardization procedures are testing and qualification protocols for MMAM parts. Established protocols have proven challenging in the past since parameters are not directly transferable when changing the geometry. However, physics-based approaches like those that are presented in [161] are helpful in bridging the gap. The presented method is based on the thermal history with the aim of assuring comparable thermal properties when transferring to other geometries. Investigations of this kind are needed in the future, since MMAM parts can exhibit almost arbitrary thermos-physical properties, levering the demand for models and simulations for an improved transferability.

First standardization approaches for e.g., round robin tests were implemented or at least recommended [150]. These test protocols should be adapted for MMAM to assure that manufacturing parameters are comparable in all cases. Thinking further, international standards such as ISO/ASTM 52901 (Additive Manufacturing – General principles – Requirements for Purchased AM Parts) or DNV-ST-B203 (Additive manufacturing of metallic parts) need to be expanded to include and consider MMAM parts [95]. Otherwise, industry will face significant issues that hinder the adaption of MMAM in the future.

For post-processing, established knowledge on e.g., the machining of additively manufactured parts can act as a reference [212]. Nevertheless, these findings need to be expanded to multi-material parts since graded or intermixed structures result in locally varying material properties [46]. Developing adequate post-processing strategies is therefore a task that needs to be addressed in the future.

5. Summary and conclusions

This keynote paper has explored the state-of-the-art in metal Multi-Material Additive Manufacturing (MMAM). While significant contributions are evident and nascent approaches are emerging which will likely influence industrial practice in the future, there remains a significant opportunity for researchers to investigate and create the design tools and machine tools which will deliver products which benefit from MMAM. The need for these is immediately obvious with respect to the case studies explored here. Research in design and machine tool technology will not advance the field alone and the role of the materials scientist will be crucial.

The current state-of-the-art from the literature reviewed here is summarized in Table 1 where authors have attempted to provide a summary at glance across process type and materials in question.

In describing what is possible and what is not from physical first principles, the design process for MMAM will mature. The volume of decisions to be made when coupling complex geometry with continuum material systems will be expanded by computational approaches. It may be that these will be rationalized through the use of defined recipe sets, but this in itself will not unlock MMAM as an industry changer.

Of particular interest to scholars in this field are the new paradigms in design which become possible. Ashby charts are widely used to compare and contrast material property “trade-offs”, yet the use of MMAM ameliorates these compromises to some degree if used correctly.

Upon reflection, the current class of MMAM technologies may be considered solutions looking for problems. Exploration of materials and processes is often patchy and often without an intended application in mind. The ability to combine contrasting material systems in monolithic components continues to inspire yet the technology is lacking in terms of capability to deliver, application-ready components without significant development.

This gives rise to technological challenges which must be addressed in order to extend the utility and hence adoption of MMAM. These are summarized below and it is hoped researchers will seize upon these directives to strengthen the field of research.

Material miscibility – Throughout the work surveyed here this presents repeatedly as a significant challenge. Where a weld in the traditional sense cannot be assured there is a need to include mechanical design approaches which result in overall part integrity. On occasion, in the literature, AM researchers have pursued material combinations which are known not to weld or on the contrary to deliver the properties in combination which maybe sought after. It is therefore necessary to explore simple approaches to explore material unions such as spark plasma sintering to understand these effects in coupon format.

Application/product-focused research – A feature of this review has been the exploration of the need for MMAM. While it is clear that impact can be felt in some key industries, this is not always immediately obvious. This is perhaps similar to topology optimization. While these computational methods are well understood it has resulted in few widespread use cases. This is in part due to the modest performance return that can be achieved. With this in mind it is clear that MMAM will also need to find niches ahead of more mainstream acceptance and development.

Control, monitoring and quality – The performance of current class mono-material AM systems is far from ideal with hype exceeding reality by some margin. Control and monitoring is clearly lacking in most systems and thus prevents AM systems from delivering high-integrity parts with assurance – essential to high-value sectors. Many of the machine developments for mono-material AM will also seemingly benefit MMAM in due course, but assessing the quality of

Table 1
A summary of capabilities and maturity of the technologies explored here.

Process used	Material combinations explored/proposed	Application(s) proposed	Typical resolution	TRL proposed	Reference
LPBF	Hard steel + copper	Injection moulding tool concept	High	Mid	[201]
	Copper CW106C + heat-resistant steel 1.2709	Injection nozzles for large bore engines	High	Mid	[209]
	Cu + CuCrZr + tungsten	Plasma-facing components for nuclear fusion reactors	High	Low	[268,223,151, 101]
	Ni-based superalloy (2.4668) + Ti6Al4V, Ni-based superalloy (2.4668) + stainless steel, Ti6Al4V graded with Cu10Sn, CoNiCrAlY coating + Ni-based superalloy, tungsten graded with stainless steel	Aeroengine components: e.g., turbine blade concept, aircraft-engine disks, protective coating, hardness and radiation shielding	Mid to high	Low to mid	[200,197,126,127,282,32,124]
	Titanium + tantalum, Ni-based superalloy + copper alloy, copper-chrome-zirconia + tool steel	Aeroengine components / rocket engine design	Mid to high	Low	[245,259]
	Ni-based superalloy + stainless steel	Heat exchanger	High	Mid	[260]
	Stainless steel + copper	Heat sink structure / Heat exchanger	Mid to high	Mid	[120]
	Ni-based superalloy + copper	Burner nozzle	High	Low	[192]
	Particle-reinforced metals	Lightweight structural components	Mid to high	Mid	[100,40,39,261]
	Ni-Fe alloy + (stainless) steel	Satellite components with a near zero CTE	Mid to high	Low	[278,11,270]
EBM	Stainless steel + Ni-based superalloys	Parts for nuclear fission applications	Mid to high	Low	[84]
	Stainless steel + copper + Ti6Al4V	Heat exchanger	Mid to high	Low	[285]
EBM + CS	Ti6Al4V + Ni-Fe alloy	Optical support structure for a nano satellite application	Low	Low	[140]
DED	High-entropy alloys (AlCoCrFeNi)	Laser cladding for protective coatings	Mid	Mid	[247]
	Low cost steel grades + Ni-based (2.4856) coatings	Aeroengine components, widespread industrial usage	Low to mid	Low	[2]
	Stainless steel + Ni-based superalloy (2.4668), Ti-Si-N ceramic coating + Ti	Aeroengine components, wear resistance coating	Low to mid	Low	[197,282]
	Stainless steel or Ni-based superalloy (2.4856) + copper alloy	Heat exchanger	Low to mid	Low	[[259,269,170]]
	Particle-reinforced metals	Lightweight structural components	Mid	Mid	[45,44]
	High-speed steel (HSS) + cobalt-based tungsten carbides WC—Co	Carbide tool insert for cutting tool	Low to mid	Mid	[215]
WAAM	High-strength steel + stainless steel + Cu-Al alloy	Holding ring as a part of the cut-off valves of hydraulic dams (1.2 m in diameter, 290 kg)	Low	Mid	[242]
Laser texturing + hot pressing	Ni-based superalloy (2.4668) + aluminium alloys	Heat extraction aerospace applications	Mid to high	Low	[128]
CS AM	Steel + Al + Ni	Heat sink structure	Mid to high	Low to mid	[38]
Extrusion + microwave sintering	Ag + Ag-Mo oxide	Single component wideband monopole antenna	Mid to high	Low	[69]
Selective laser burnout	Ag + Bi-Mo	RF and microwave communication components	Mid to high	Low	[64]
Inkjet printing	Dielectric + conductive inks (containing metal particles)	Circuit boards and antenna elements	Mid to high	Low	[243,179]
Miscellaneous	Polymers, metals as well as cermets and ceramics	Energy conversion, storage, and transportation (e.g. batteries, SOECs and SOFCs), sensors and electronics integration	Mid to high	Low	[69,219,178, 277,141,37,109]

multiple materials within a volume will place a new burden on the tools and methods we commonly use.

1) Design processes – To exploit MMAM it is clear that advanced design processes are required. Some inroads to modelling, data management and geometry realization have been reported in the literature but the tools required to deliver proper designs are not yet readily available and/or widely understood. This will require remedial attention to secure industrial acceptance of MMAM.
2) Sustainability – Based on the evidence presented in this review it is clear that multiple materials embedded in the same volume will create a more complex waste stream and the technology does not yet exist to recover value easily at the end of life. While superior MMAM components may extract better through life from their embedded carbon than conventional counterparts, this seems like a distant possibility at this time.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

A.T. Clare: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **P. Woizeschke:** Writing – review & editing, Writing – original draft, Conceptualization. **B. Rankouhi:** Writing – original draft. **F.E. Pfefferkorn:** Writing – original draft. **D. Bartels:** Writing – original draft. **M. Schmidt:** Writing – original draft. **W.W. Wits:** Writing – review & editing, Writing – original draft, Conceptualization.

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